AFWAL-TR-86-2015

ADVANCED HIGH-POWER GENERATOR RESEARCH PROGRAM

AiRESEARCH MANUFACTURING COMPANY
2525 W. 190th STREET
TORRANCE, CALIFORNIA 90509

MAY 1986

FINAL REPORT FOR PERIOD JANUARY 1984 - OCTOBER 1985

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This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes work accomplished in phase III of the advanced high-power generator research and development program, F33615-76-C-2168, part of an Air Force exploratory development program for high-power airborne electrical power supply technology. The program includes the design of a 5-mw generator for use in a 10-mw power supply and fabrication and testing of the generator rotor. The five program phases are: phase I, design; phase II, critical component testing;

20. ABSTRACT (Continued)

phase III, rotor fabrication; phase IV, rotor testing; and phase V, test plan preparation.

The overall objective of the exploratory development program is to demonstrate through prototype hardware testing, that an ultralightweight (0.1 lb/kw), nonsuperconducting generator can be successfully built in the 1-to-10-mw power range.

The program was terminated at the end of phase III. This report covers the fabrication of a samarium-cobalt permanent magnet rotor which included: HIP- (hot isostatic pressure) bonding, heat treating, machining, magnet assembly, sleeve installation, and spinning.

FOREWORD

This report summarizes the work accomplished in phase III of the advanced high-power generator research program, contract F33615-76-C-2168, sponsored by the Power Systems Branch, Aerospace Power Division, of the Aeropropulsion Laboratory, Air Force Wright Aeronautical Laboratory, at Wright-Patterson Air Force Base.

At Wright-Patterson, the program is under the technical direction of Captain Neal Harold. At AiResearch, Fred B. McCarty is the principal investigator, Andrew R. Druzsba is the project engineer, and Tracy E. Johnson is the program manager. Special acknowledgement is given to Dr. Tom Long-Freh Lee, Dr. Ahmed Hammoud, and Paul E. Gassen.

This report does not contain proprietary information. Tape out any statements pertaining thereto.
Per Ms. Evelyn Foster, AFWAL/GLIST

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1. INTRODUCTION

This report describes the process used to fabricate a 5-mw rotor.

The report summarizes work accomplished in phase III of the advanced high-power generator research and development program F33615-76-C-2168. This effort is part of an Air Force exploratory development program on high-power, airborne, electrical power supply technology. The program includes the design of a 5-mw generator for use in a 10-mw power supply, and fabrication and testing of the rotor portion of that generator. The overall objective of the program was to demonstrate through prototype hardware testing that an ultra-lightweight (0.1 lb/kw), nonsuperconducting generator can be successfully built in the 1- to 10-mw range.

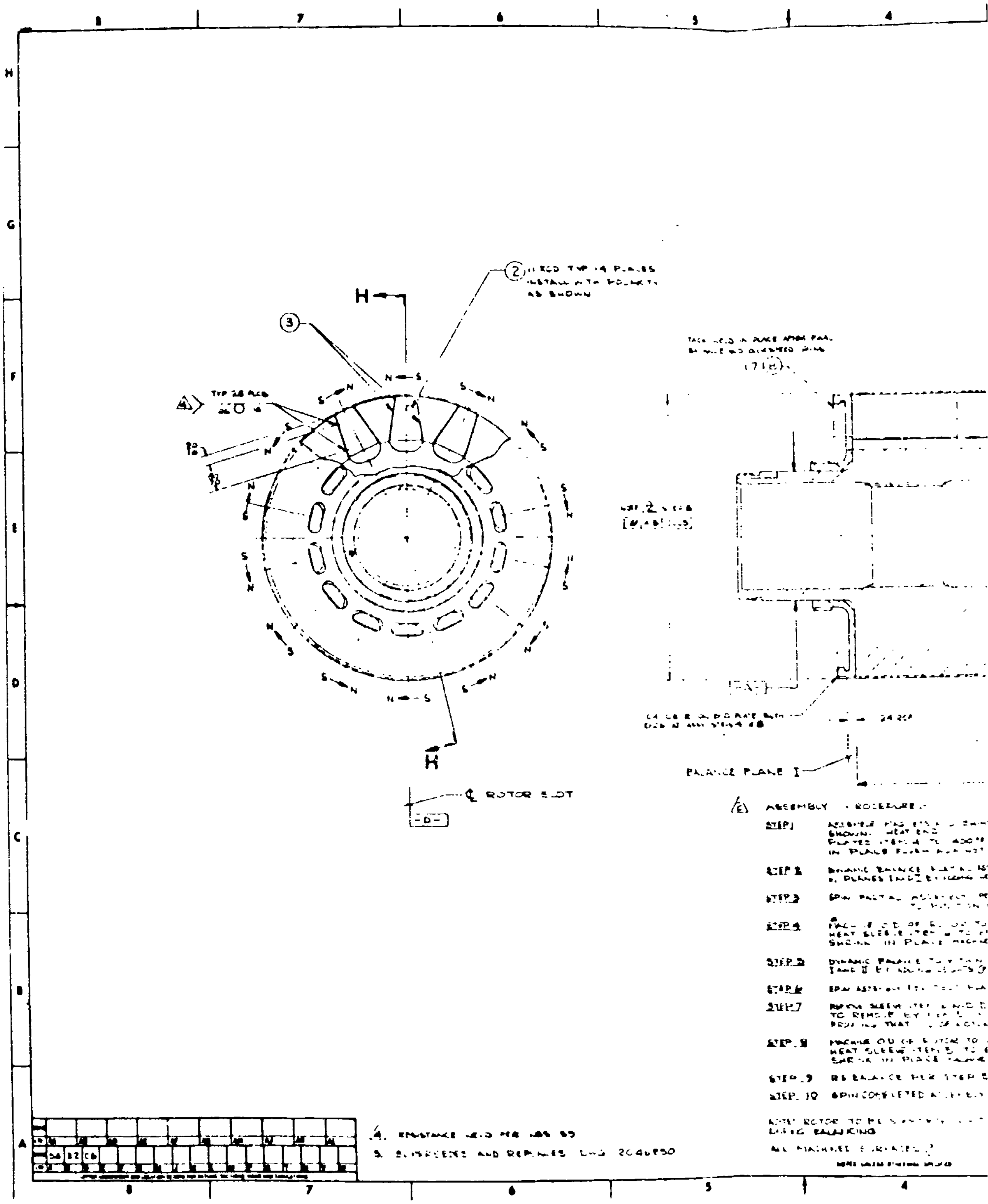
Plans called for five phases:

- Phase I, Design
- Phase II, Critical Component Testing
- Phase III, Rotor Fabrication
- Phase IV, Rotor Testing
- Phase V, Test Plan Preparation

However, the Air Force has decided not to complete the remainder of phase III or phase IV. Magnet failure in the final stages of assembly suggested that further work, at this point in the development of the technology, would not be cost-effective.

2. ROTOR DESCRIPTION

The basic rotor structure consists of an inner Inconel 718 cylinder HIP (hot-isostatic-pressure)-bonded to an HP 9-4-20 outer tube. Fourteen equally spaced, wedge-shaped slots are machined in the periphery of the bonded rotor to accommodate the samarium cobalt permanent magnets. Soft, perforated, nickel shims are inserted at each interface between the magnet and rotor slot surface to compensate for nonuniformities. The type of material and the perforation patter for the shims were determined during IR&D testing performed at AiResearch. After the magnets and shims are inserted in the slots, the rotor is spun to 300 fps to seat the magnets. The outer diameter is then ground to an in-process dimension, and a sleeve is shrink-fitted over the rotor assembly. The Inconel sleeve is ground to 0.032 in. thick, and the rotor overspun to operating speed +10 percent (19,800 rpm) to allow the magnets to move to maximum extended position and lock in place. The first sleeve is then removed and the rotor ground to final diameter. A second Inconel sleeve retains small magnet particles that may chip at high speed or under thermal stress and prevents them from entering the small gap between the rotor and stator. The sleeve also acts as an electrical damper, minimizing the effects of armature reaction on rotor flux. The complete rotor assembly is shown in Figure 2-1. A complete set of drawings appears in the appendix.



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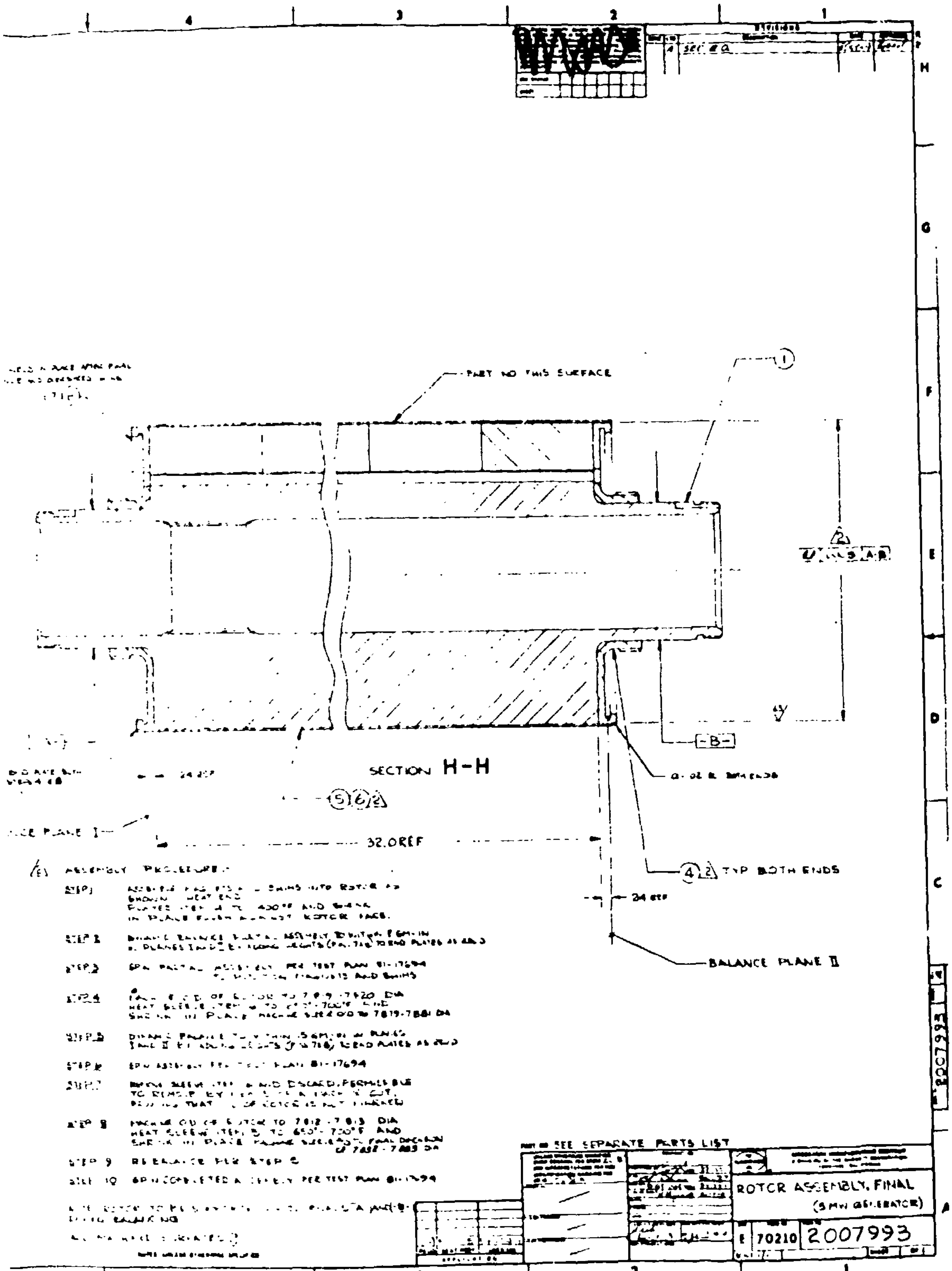


Figure 2-1. Final Rotor Assembly

3. HOT ISOSTATIC PRESSURE (HIP) BONDING

Four attempts to HIP-bond (hot isostatic pressure bond) full-length rotor assemblies were required before a successful bond was made. Table 3-1 shows procedures used up to the last attempt.

The fourth and final successful method is detailed below.

Detail hardware was dry machined and vapor degreased at the AiResearch Western Avenue facility. The HP 9-4-20 sleeve was shipped to California Technical Plating for Watts nickel plating. The unit was bagged and purged with dry nitrogen within 3 hr of plating.

The Inconel 718 sleeve was dry machined using a Carboloy TPMM 322 E 46, grade 895, machine tool insert with the workpiece spinning at 95 rpm and an 0.013 in./min feed rate.

The unit was assembled the following day. One end plate was welded to the assembly. Inconel 718 powder (5.5 lb), supplied by Industrial Materials Technology, was added to the interface between the assembled sleeves. The end plate was welded to the top, and the unit was checked for helium leaks (see Figure 3-1). A leak was detected and repaired (see Figure 3-2). Figure 3-3 shows the final configuration of the welded assembly.

The unit was backfilled with dry nitrogen at 20 psi and shipped in an upright position to Industrial Materials Technology, Inc. in Andover, Massachusetts. At Industrial Materials Technology the unit was heated and evacuated for two days prior to placement in the pressure vessel. A temperature vs pressure chart is shown in Figure 3-4 to present the actual HIP cycle used. In addition, a time-phased summary of activities leading to the successful bond is shown in Table 3-2.

The positive results obtained from the fourth HIP-bond attempt were attributed to the long, slow heatup and cooldown times. The high strength of the bond is thought to be a direct result of the Inconel 718 powder being used in the gap between the dissimilar metals.

3.1 TEST SAMPLES

3.1.1 Ring Segment Removal

Two ring segments were removed from the HIP-bonded rotor assembly, one from each end, as shown in Figure 3-6.

The first step in this process was to machine off the welded end rings sealing the interface between cylinders for HIP-bonding. The ends of the HIP-bonded cylinders after machining are shown in Figure 3-5.

TABLE 3-1

HIP CYCLES RUN DURING MOTOR PROGRAM

CASE NO.	BONDING DATE	MATERIAL INNER	MATERIAL OUTER	LENGTH (IN.)	DIA. (IN.)	HIP FACILITY	FINAL SURFACE PREPARATION	CONTAINER TYPE
1	11-29-78	INCO 625	HP9-4-20	2.4	8.0	IMT	DRY MACHINING	INCO 625 END RINGS
2	5-3-79	INCO 718	HP9-4-20	2.4	8.0	IMT	DRY MACHINING	INCO 625 END RINGS
3	5-7-79	INCO 718	HP9-4-20	2.4	8.0	IMT	DRY MACHINING	INCO 625 END RINGS
4	5-8-79	INCO 718	HP9-4-20	2.4	8.0	IMT	DRY MACHINING	INCO 625 END RINGS
5	4-1-81	INCO 718	HP9-4-20	40.0	8.0	IMT	ACID ETCH	INCO 625 END CAPS
6a	11-9-81	INCO 718	HP9-4-20	38.5	8.0	BATTELLE	ABRATING/ALCOHOL	304 STAINLESS CAN
6b	11-9-81	INCO 718	HP9-4-20	1.25 X 2	8.0	BATTELLE	ABRATING/ALCOHOL	304 STAINLESS CAN
7a	2-23-82	INCO 718	HP9-4-20	38.5	8.0	BATTELLE	ABRATING/ALCOHOL	INCO 625 CAN
7b	2-23-82	INCO 718	HP9-4-20	1.25	8.0	BATTELLE	ABRATING/ALCOHOL	INCO 625 CAN
7c	2-23-82	INCO 718	HP9-4-20	1.25	8.0	BATTELLE	ABRATING/ALCOHOL	INCO 625 CAN
8a	PROPOSED	INCO 718	HP9-4-20	1.25	8.0	IMT	DRY MACHINE	END RINGS
8b	PROPOSED	INCO 718	HP9-4-20	1.25	8.0	IMT	DRY MACHINE	END RINGS

MOTOR PROGRAM

CONTAINER TYPE	BOND PARAMETERS			OUTCOME	GAP X.001 IN.
	PRESS	TEMP. °F	TIME (HRS.)		
NCO 625 END RINGS	15000 PSI	2100	4	SUCCESSFUL BOND	2-3
NCO 625 END RINGS	15000 PSI	2100	4	SUCCESSFUL BOND	2-3
NCO 625 END RINGS	15000 PSI	1950	4	SUCCESSFUL BOND	2-3
NCO 625 END RINGS	15000 PSI	1800	4	SUCCESSFUL BOND	2-3
NCO 625 END CAPS	15000 PSI	1800	4	CONTAINER LEAK	8-10
304 STAINLESS CAN	30,000 PSI	1950	3	CONTAINER LEAK	12-21
304 STAINLESS CAN	30,000 PSI	1950	3	NO BOND	12-14
INCO 625 CAN	18,000 PSI	1950	3	NO BOND	6-8
INCO 625 CAN	18,000 PSI	1950	3	CONTAINER LEAK	6-8
INCO 625 CAN	18,000 PSI	1950	3	NO BOND	6-8
END RINGS	15,000 PSI	1800	4	—	6-8
END RINGS	15,000 PSI	1800	4	—	12-14

A 27219

2

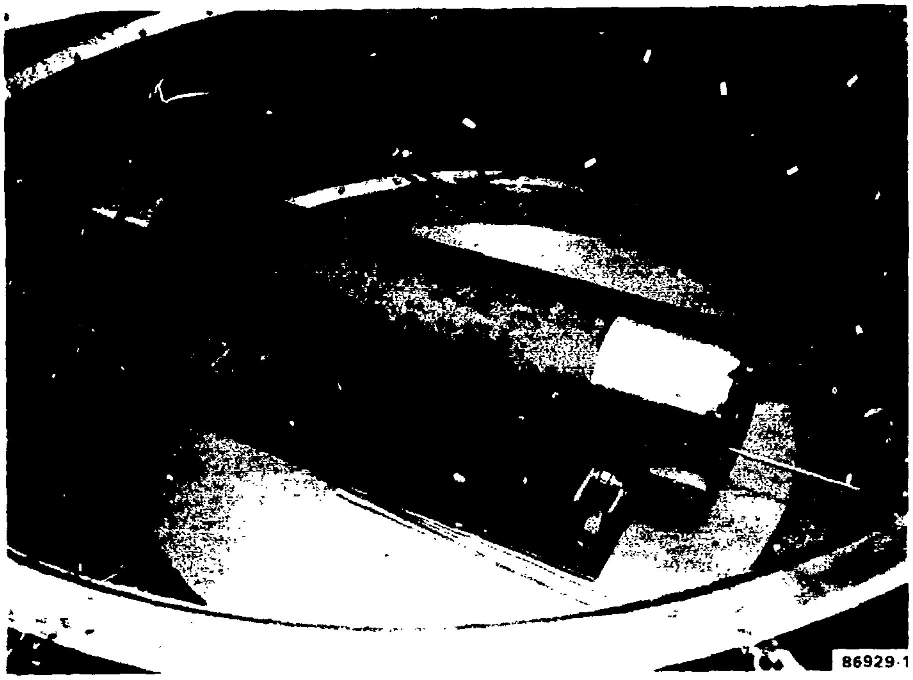
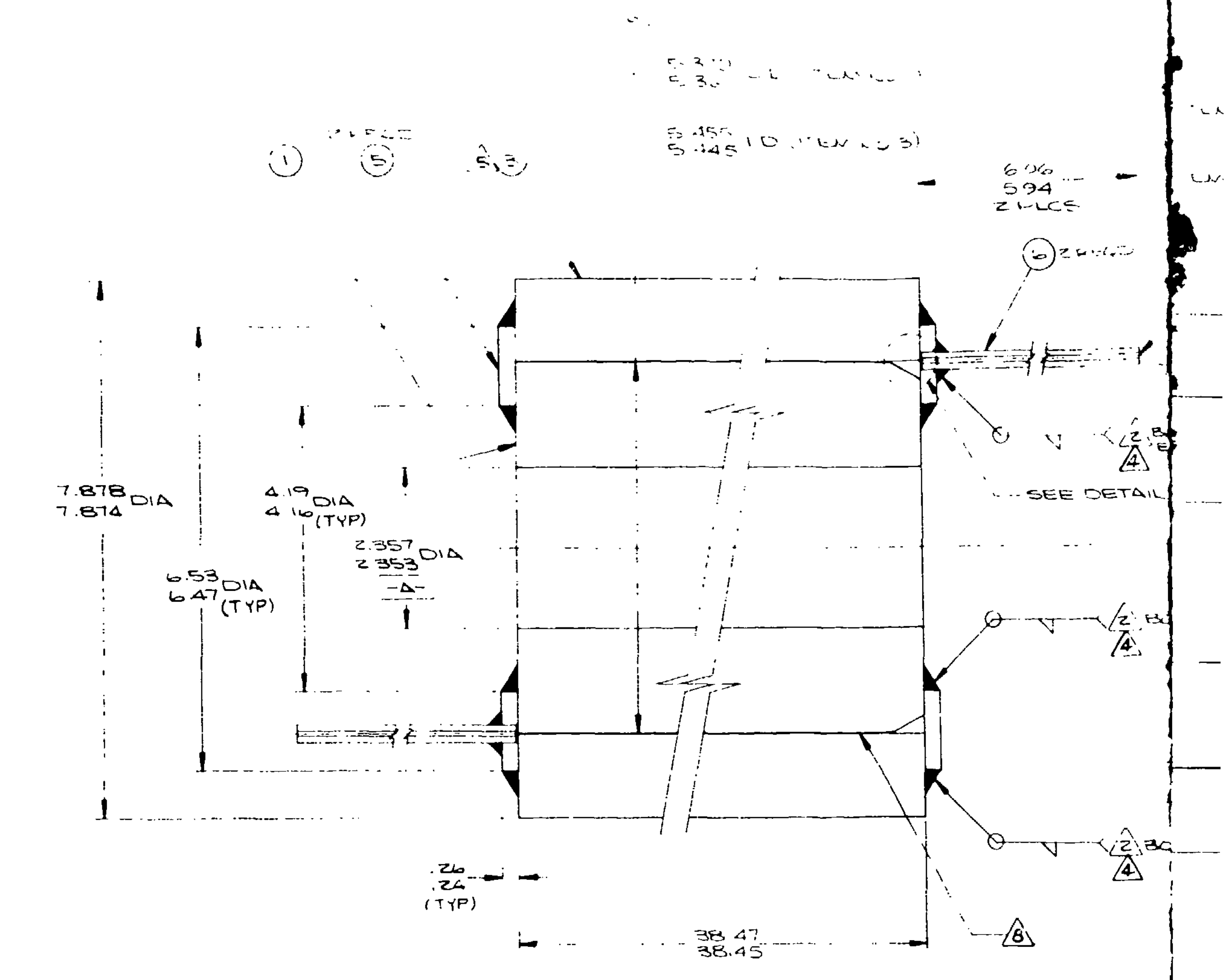


Figure 3-1. Rotor Assembly on Rotary Fixture in Welding Bubble

Figure 3-2. "B" End of Rotor Assembly with Repaired Leak in Outer Weld

K-10464



8. FILL JOINT WITH INCO 718 POWDER PER PROCEDURE 82-19072 THEN CHECK WELDS PER NOTE 4. THEN FILL JOINT NOTED WITH DRY NITROGEN GAS AT 20 PSIA FOR SHIPMENT.

7. ASSEMBLY, WELDING, LEAK CHECK, NITROGEN FILL AND SEALING MUST BE PERFORMED WITHIN 8 HOURS OF MACHINING 5.45 NOM DIA.

6. FINAL MACHINING (DO NOT GRIND) SHALL BE PERFORMED ONLY AFTER ALL PARTS HAVE BEEN DEGREASED AND DRIED. NO CONTACT WITH MACHINED SURFACES AFTER FINAL MACHINING IS PERMITTED. FINISHING MACHINE TO BE CLEAN AND FREE OF OIL (USE NO CUTTING FLUID) SEE HIP BOND PROCEDURE 82-19072.

5. I.D. OF ITEM NO. 3 HAS BEEN NICKEL PLATED .0005-.001 THICK (WATTS NICKEL PER QQ-N-290) TO ENHANCE DIFFUSION.

4. HELIUM LEAK CHECK WELDS PER HIP BOND PROCEDURE 82-19072 SHALL NOT EXCEED 6 TO 8×10^{-10} STANDARD CC/SECOND.

3. VAPOR DEGREASE PRIOR TO WELD PER C10.

2. WELD PER WBS 18 USING HASTALLOY W ROD PER MIL-R-5031, CL 12

1. FINISH ALL OVER $\sqrt{125}$.

NOTES: UNLESS OTHERWISE SPECIFIED

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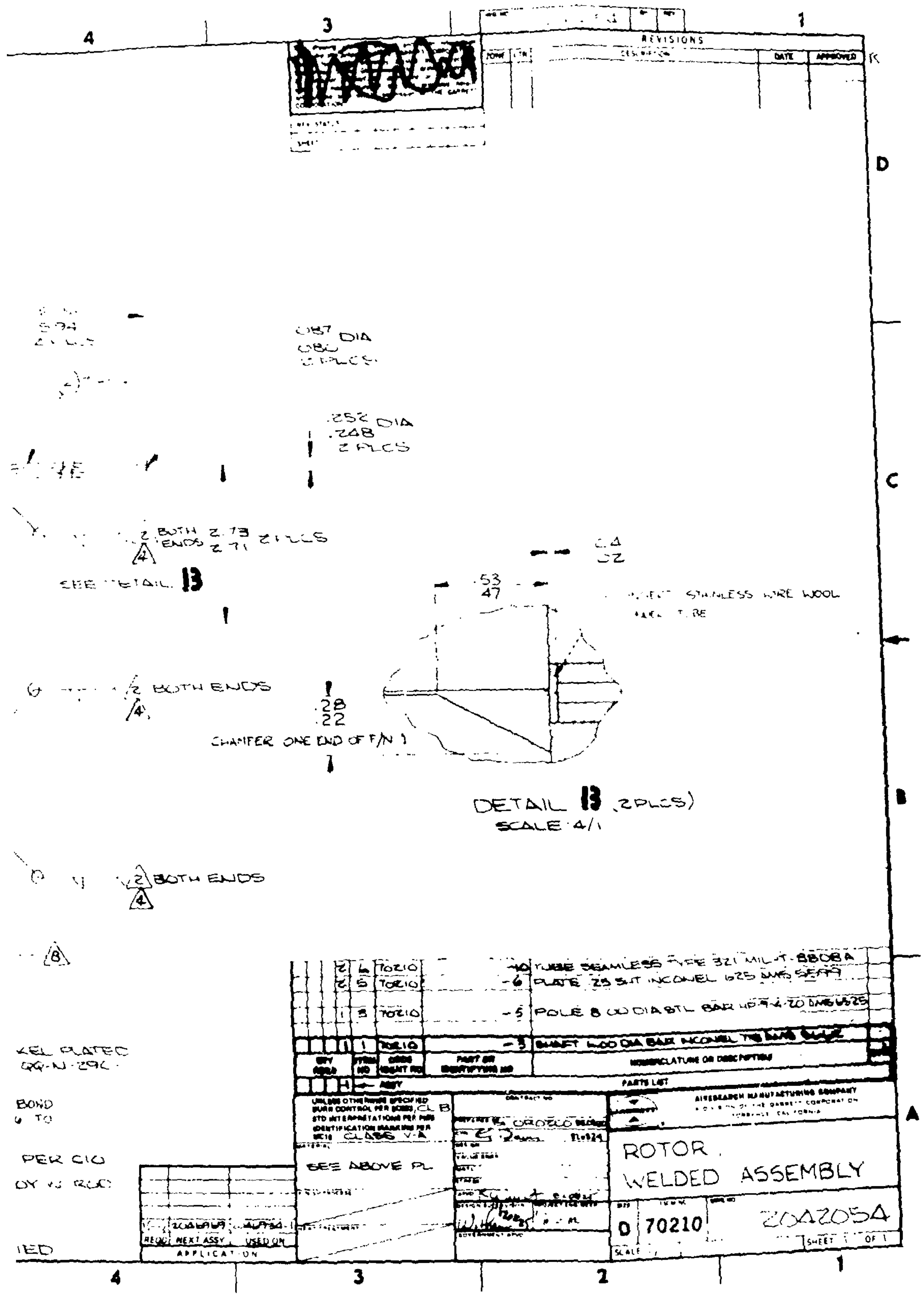

Figure 3-3. Rotor Welded Assembly

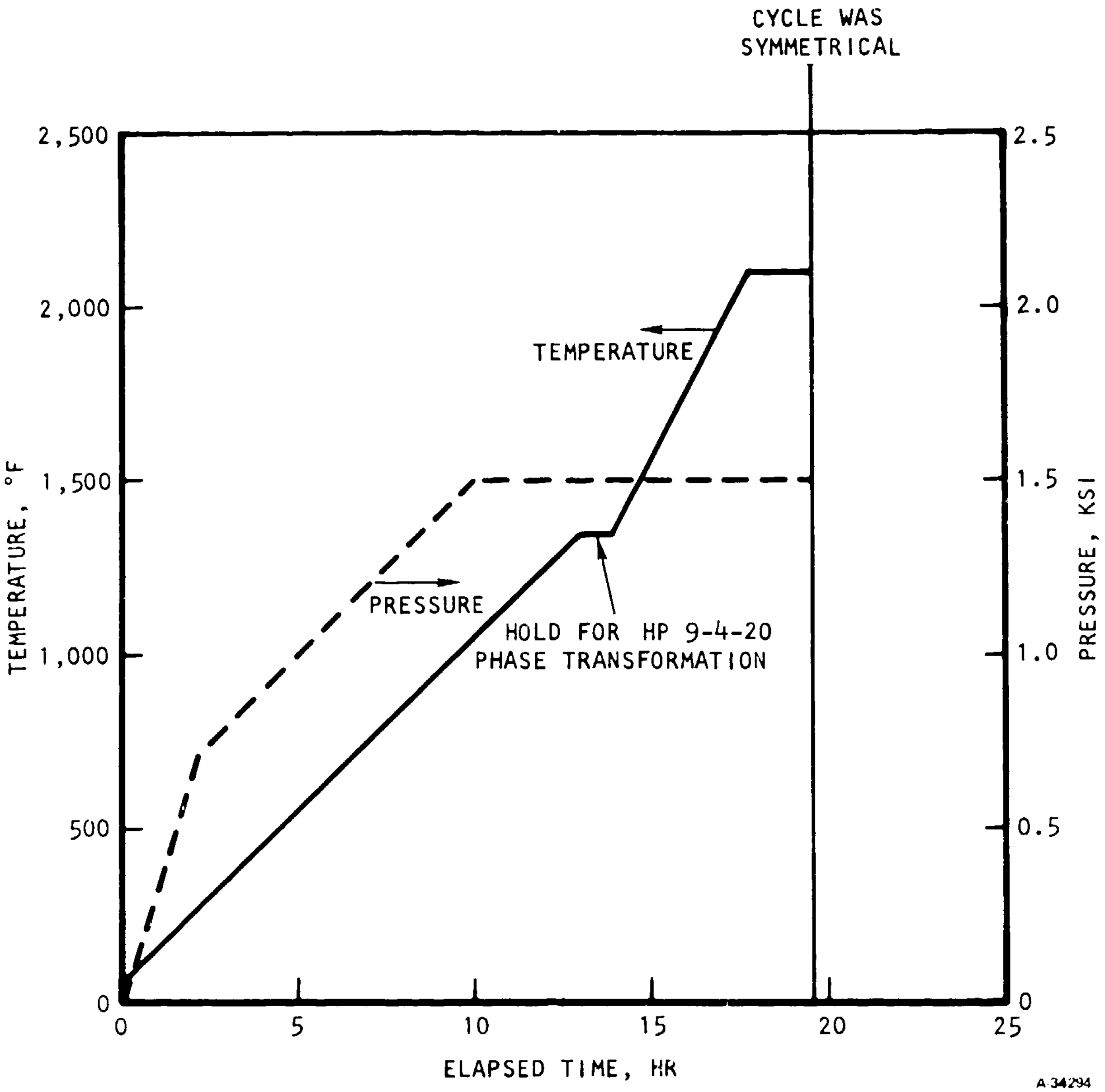

Figure 3-4. Temperature vs Pressure Time For Fourth HIP Cycle At Industrial Materials Technology, Inc., September 16, 1982

TABLE 3-2

HIP-BOND PROCEDURE SUMMARY OF SEPTEMBER 16, 1982

Procedure	Date
HP 9-4-20 cylinder nickel-plated	September 7 Tuesday
Inconel 718 cylinder was final-dry-machined	September 8 Wednesday
Unit assembled, filled, sealed, leak-checked, and back-filled	September 9 Thursday
Leak-welded, leak-checked, back-filled unit shipped to Industrial Materials Technology	September 10 Friday
Evacuation with heating	September 14 to 16 Tuesday to Thursday
HIP cycle	September 16 to 18 Thursday to Saturday

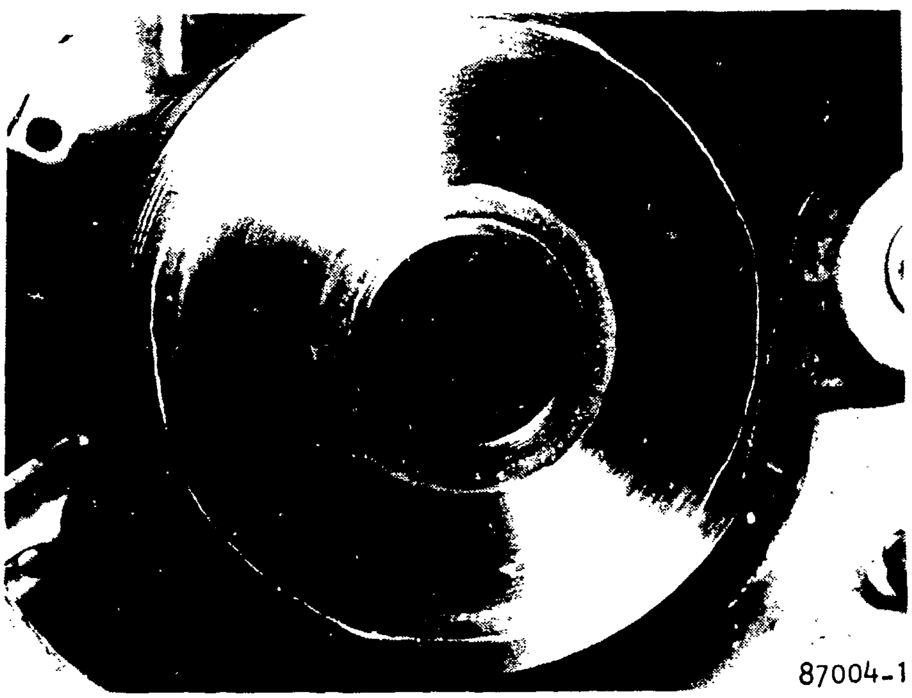

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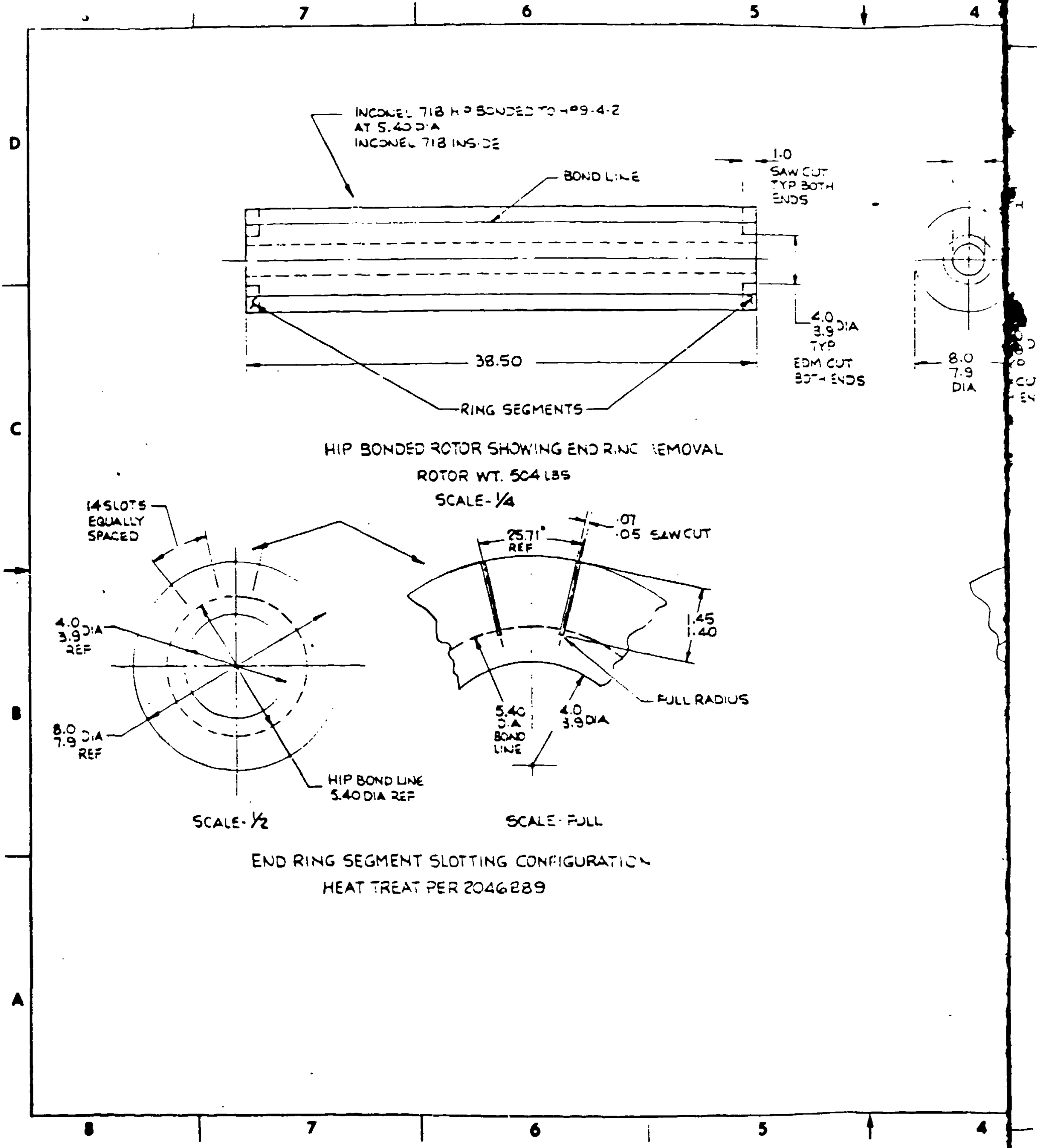
Figure 3-5. End of HIP-Bonded Cylinders



INCONEL 718 HIP BONDED TO HP9-4-2
AT 5.40 DIA
INCONEL 718 INSIDE
BOND LINE
1.0
SAW CUT
TYP BOTH
ENDS
4.0
3.9 DIA
TYP
EDM CUT
BOTH ENDS
38.50
RING SEGMENTS
8.0
7.9
DIA
HIP BONDED ROTOR SHOWING END RING REMOVAL
ROTOR WT. 504 LBS
SCALE-1/4
14 SLOTS
EQUALLY
SPACED
4.0
3.9 DIA
REF
8.0
7.9 DIA
REF
HIP BOND LINE
5.40 DIA REF
SCALE-1/2
25.71°
REF
.07
.05 SAW CUT
1.45
1.40
FULL RADIUS
5.40
DIA
BOND
LINE
4.0
3.9 DIA
SCALE-FULL
END RING SEGMENT SLOTTING CONFIGURATION
HEAT TREAT PER 2046289

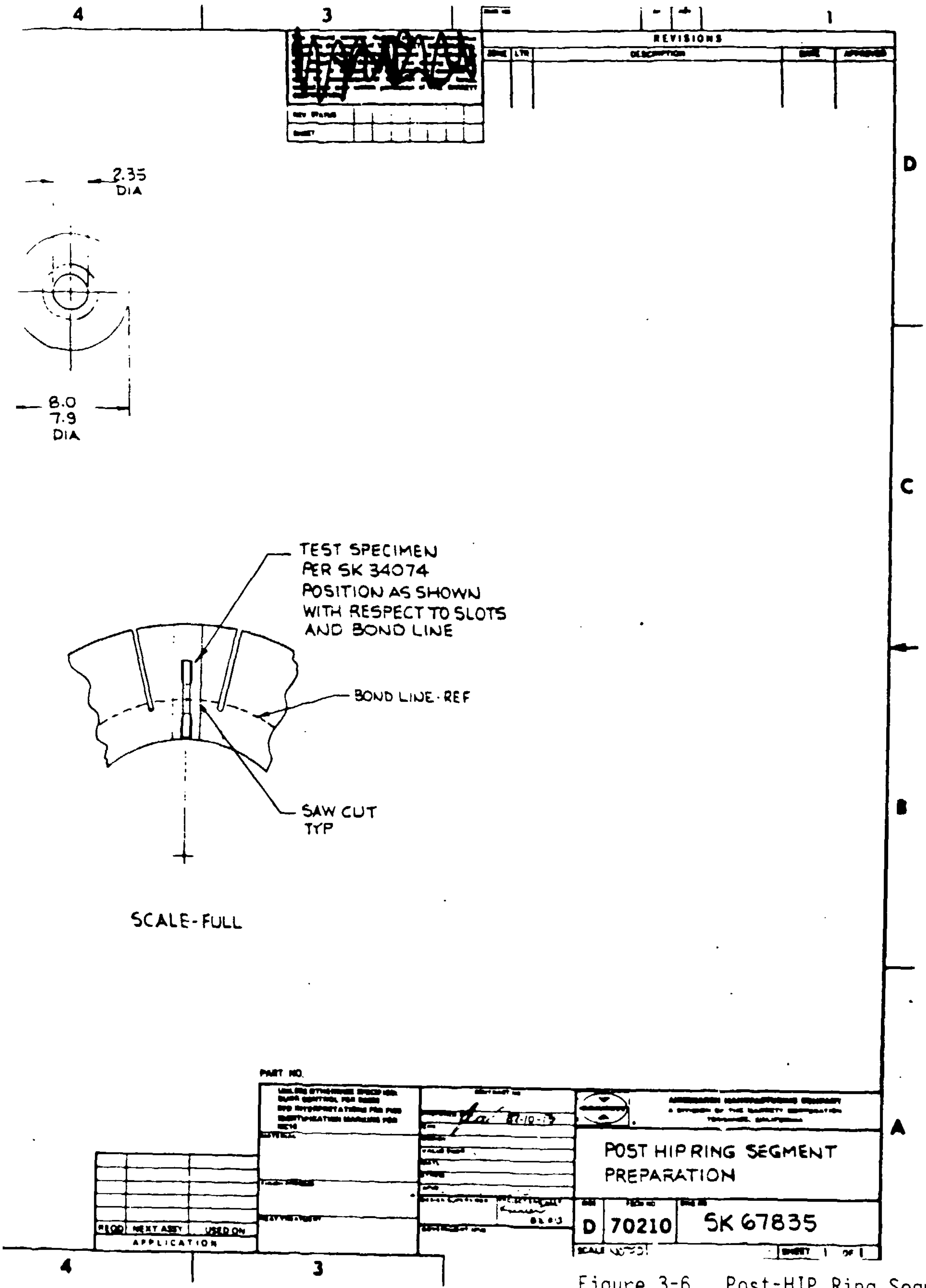


Figure 3-6. Post-HIP Ring Segment Preparation

The next step was to electric-discharge machine (EDM) a 4-in.-dia groove, 1 in. deep into each end. A saw cut from the outside diameter 1-in. in from the end was made to connect with the groove. This was necessary because the ring segment had to be removed above the diameter of the bearing journals and end stubs.

3.1.2 Ring Segment Slotting

Each of the ring segments was faced off and slotted in 14 places around the periphery as shown in Figure 3-6 and Figure 3-7. The slots were cut to prevent buildup of radial stresses due to differential thermal expansion during the heat-treatment cycle.

3.1.3 Heat Treatment of Ring Segments

The ring segments were heat treated at AiResearch, per specification 2046889. The heat treatment is the same one used on the short-section rotors during phase II critical component testing, with one exception. A solution anneal was added for the long rotor assembly because of the extremely slow cooling used for the HIP cycle. The ring segments are shown in Figure 3-7 after heat treatment.

3.1.4 Tensile Specimen Testing

The heat-treated ring segments were cut into pieces to provide material for tensile specimens with the bond joint alignment shown in Dwg. SK67835 and Figure 3-8. Care was taken to ensure that the centerline of the tensile specimen was perpendicular to the bond line.

A total of 24 tensile specimens were machined at AiResearch per Dwg. SK34074, 12 from the top ring segment and 12 from the bottom ring segment. The top of the rotor refers to the end at which the Inconel 718 powder was added. It is also the end where the chamfering in the Inconel 718 cylinder was performed as shown in Figure 3-3 on page 3-7 of this document.

A summary of the ultimate and yield strengths and the percent elongation for the samples is shown in Table 3-3. The data for sample T1 are not listed because the bond joint was located away from the center of the specimen. No strength is given for sample B3 due to a data error.

Specimen T6 has the lowest values of the lot and is being examined to determine the nature of the fracture. The Industrial Materials Technology samples were not heat treated, as were the other samples, and this accounts for the differences in strength.

Micrographic inspection of samples from the ring segments supports the strength data and indicates that there is a good HIP bond between the Inconel 718 and HP9-4-20. The AiResearch materials department completed its study of the HIP-bond sample data and issued a report describing their findings. This report appears in Exhibit 3A. This report supports their conclusion that the rotor was completely and satisfactorily HIP bonded.

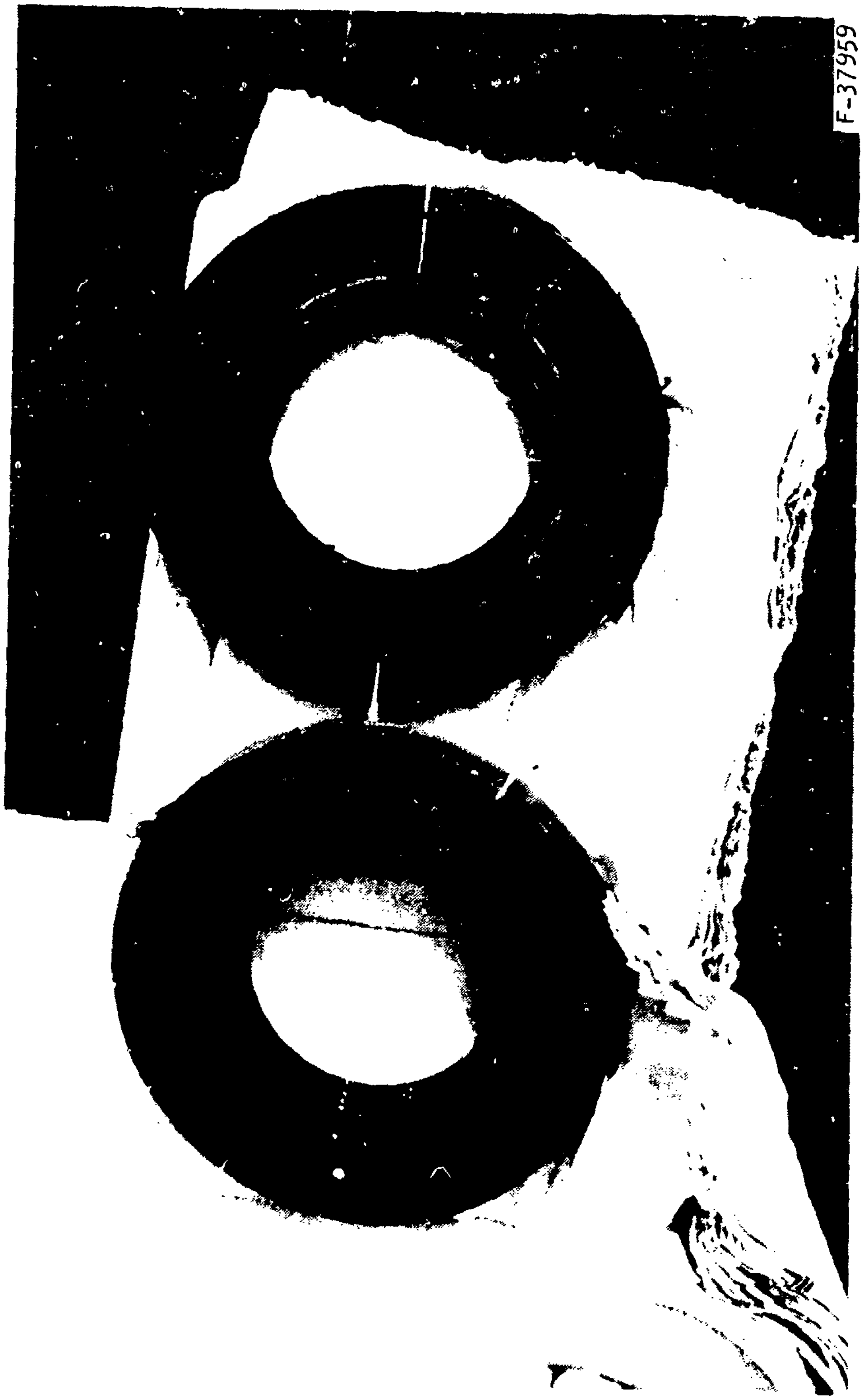


Figure 3-7. Slotted Ring Segments

K-10465

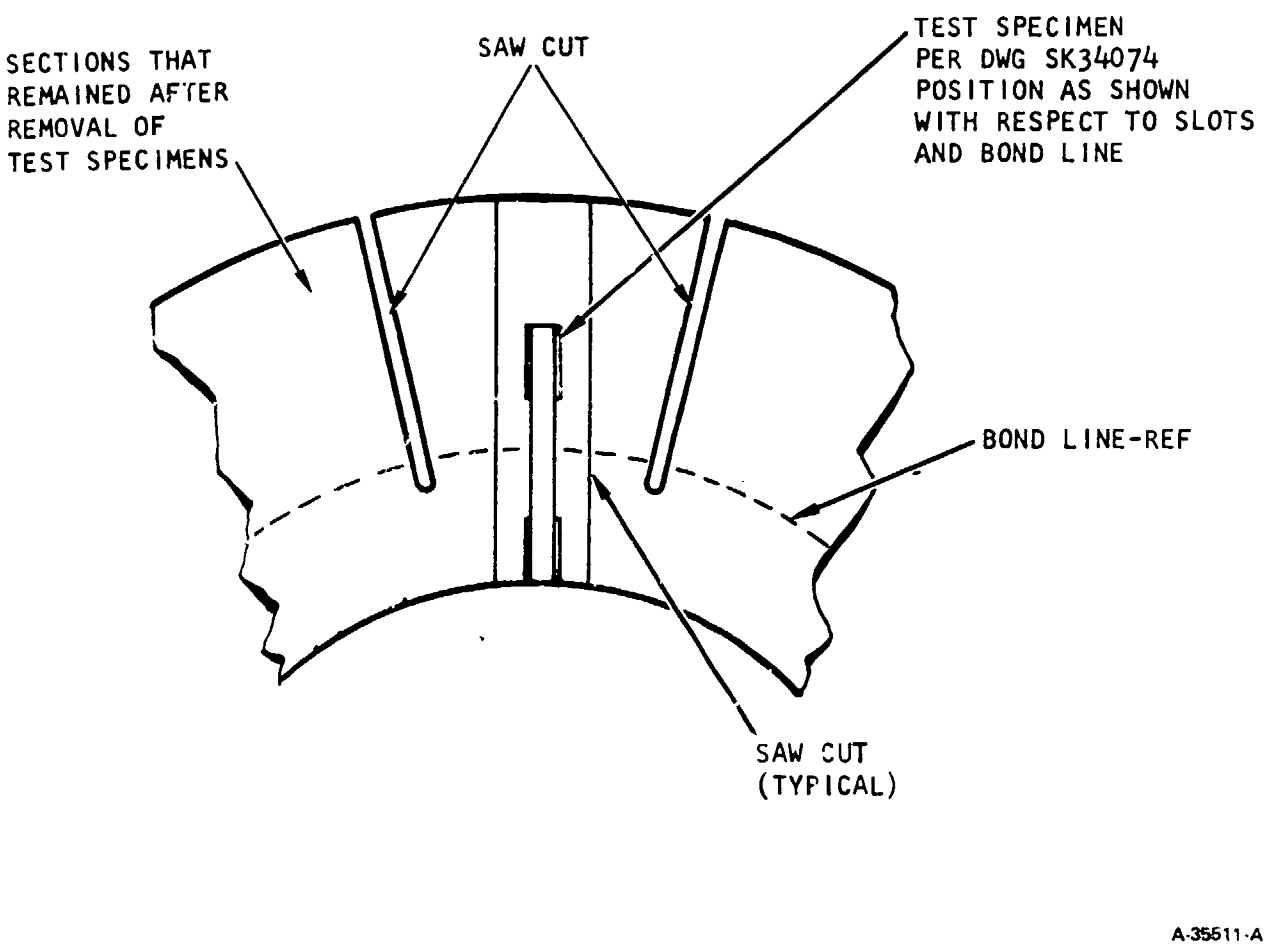


Figure 3-8. Tensile Specimen Position on Ring Segments

TABLE 3-3

TENSILE SPECIMEN RESULTS FOR SEPTEMBER 1982
HIP BOND OF FULL-LENGTH ROTOR ASSEMBLY*

KSI			
Sample	Yield	Ultimate	Elongation, percent
T1	---	---	---
T2	129.1	158.6	4.0
T3	133.2	158.2	4.0
T4	129.5	159.0	4.0
T5	128.3	161.1	4.0
T6	120.0	125.0	1.0
T7	135.4	164.1	4.0
T8	126.7	161.1	4.5
T9	129.1	159.2	4.0
T10	135.4	162.9	4.0
T11	122.9	156.2	4.0
T12	127.0	159.0	4.0
B1	129.2	160.2	4.0
B2	129.1	161.9	4.0
B3	---	154.1	4.0
B4	125.0	156.9	4.0
B5	128.7	155.8	3.5
B6	127.1	156.7	3.5
B7	129.2	158.7	4.0
B8	128.7	161.7	4.0
B9	125.8	155.7	4.0
B10	131.1	161.2	4.5
B11	130.8	160.0	4.5
B12	130.4	154.2	4.0

*2100°F, 15,000 psi, IMT, Inc., September 16, 1982.

EXHIBIT 3A

CHEMICAL & METALLURGICAL
REPORT 15278-2

Mat'l Engrg Ref. Nos

AIRESEARCH MANUFACTURING DIVISIONS
Los Angeles · Phoenix
CHEMICAL & METALLURGICAL REPORT
(REQUESTOR TO FILL IN BETWEEN DOUBLE LINES)

CMR LA NUMBER
CMR PHX NUMBER

PART NAME ROTOR HIP
PART NUMBER 2042054
DATE 10-18-82
DATE RECD
PROBLEM STATEMENT
SAMPLE DESCRIPTION 2 sections
HEAT NO
ALLOY & COND INCO 718/9-4-20
SPECIFICATION
SIZE
QUANTITY
RECEIVING REPORT
PURCHASE ORDER
REF. ENG. NO 3205-888007-82-0300
SUPPLIER
BUYER

Determine mechanical properties after HT per AF642
AF642

COPIES TO ANDY DRUZSBA
REQUESTOR D. MCGRATH
PROJECT HIP
DEPT 93-7

TENSILE TEST				HARD	IDENT
ULTIMATE	YIELD	ELONG	RA		

EFFECTIVE CASE DEPTH

REQUIRED ON MOL	REQUIRED ON R.T.	ACTUAL

HARDNESS DATA

CASE		CORE	
REQUIRED	ACTUAL	REQUIRED	ACTUAL

MICROHARDNESS TRAVERSE IN INCHES FROM EDGE Rc

CHEMICAL ANALYSIS

Al			
Sb			
Be			
B			
Cd			
C			
Cr			
Co			
Cb			
Cu			
Fe			
Pb			
Mg			
Mn			
Mo			
Ni			
P			
Si			
Ag			
S			
Te			
Sn			
Ti			
W			
V			
Zn			
Zr			

-SEE ATTACHED REPORT-

RECOMMENDED DISPOSITION:

BY D.W. McGrath DATE 11/2/82
MATERIALS & PROCESS ENGINEERING

INTRODUCTION

Discs, cut from top and bottom ends of a HIP diffusion bonded generator rotor, P/N 2042054 were submitted for metallurgical analysis. The rotor was HIP diffusion bonded at IMT on September 16-17, 1982. The Inconel 718 and HP 9-4-20 cylinders were assembled at AiResearch Manufacturing Company on September 8 and 9 with Inconel 718 powder between the mating surfaces. Prior to assembly, the HP 9-4-20 outer cylinder was electroplated with high purity nickel to provide a diffusion barrier for carbon from the HP 9-4-20 steel. To minimize the detrimental effects of volumetric expansion of the steel during cooling through the transformation range, a very slow cooling rate was used, with a temperature hold at 1350°F.

The discs were cut, one from each end, and radial slots were machined through the HP 9-4-20 from periphery and into the 718 at location corresponding to magnet pockets in the rotor. The discs were then heat treated in accordance with the drawing. The slots were machined prior to heat treatment in order to minimize radial stresses between the two alloys during cooling from solution heat treatment.

Following heat treatment, twelve tensile specimens per drawing SK 34074 (See Figure 9) and several specimens for metallographic examination were machined from each disc.

TENSILE PROPERTIES

Twenty four tensile specimens were tested. Results are shown in Table I. The results from two specimens were discarded as statistical outliers. One specimen was incorrectly machined, with the the bond interface located in the threaded area of the specimen. The other specimen sustained some machining damage which resulted in failure in an area remote from the bond interface.

The balance of the specimens displayed very little variance in strength. A statistical test, the Student's "t" test was conducted to determine if the means in strength of top versus bottom discs were different. At the 95% confidence level, there was no statistically significant difference between means of either ultimate or yield strengths when comparing top vs bottom discs. The data from both discs were therefore lumped together to calculate design minimum strengths. Both "A" and "B" basis design minimums (per MIL-HDBK-5 definitions) are shown in Table I. When more data are acquired, calculated design minimums are expected to be even higher because the penalty associated with a small number of specimens will be reduced.

MICROSTRUCTURE

Microstructure of the bond interface and photomicrographs of tensile specimen ruptures are shown in Figures 1 through 8. Bonds were continuous and nonporous and had a microstructure markedly superior to those formerly obtained. Previous bonds displayed heavy grain boundary carbide networks which undoubtedly reduced local ductility in the bond region and also reduced fracture toughness.

Previous bonds also displayed rupture pores or continuous bond failures caused by radial stresses encountered during transformation of the steel during cooling from HIP bonding temperature. The structures shown in Figures 1-6 show no pores, no bond failures, and the carbides are well spheroidized and dispersed. No difference in microstructure was evident between top and bottom discs.

Micros were also made through several failed tensile specimens. Failures occurred within the Inconel 718 carbide precipitation zone.

CONCLUSIONS

1. Superior microstructures were obtained in the latest bonding cycle.

2. Excellent bond strengths were obtained, and results showed good reproducibility.

3. The HIP procedure developed should be capable of producing high reliability hardware.

D.W.McGrath

D. W. McGrath
Materials Engineering

TABLE 3A-1

Tensile Test Results on
Rotor HIP Bond

Inconel 718 to HP9-4-20

Ident	Ident	Ultimate ksi	Yield ksi	Elong %	RA %	
A top	1527	204.0	185.4	16.0	55.6	DISCARDED (1)
A bot.	1528	160.2	129.2	4.0	13.5	
				10-18-82		
B top	1544	158.6	129.1	4.0	10.6	
B bot.	1545	161.9	129.1	4.0	12.1	
C top	1546	158.2	133.2	4.0	9.6	
C bot.	1547	154.1	150.4	3.5	7.4	
D top	1548	159.0	129.5	4.0	9.8	
D bot.	1549	156.9	125.0	4.0	10.6	
				10-20-82		
G bot.	1554	158.7	129.2	4.0	9.2	
H top	1555	161.6	126.7	4.5	10.8	
K top	1556	156.2	122.9	4.0	9.0	
L top	1557	159.0	127.0	4.0	9.1	
				10-21-82		
F bot.	1562	155.8	128.7	3.5	8.9	
F bot.	1563	156.7	127.1	3.5	9.2	
				10-22-82		
C top	1564	159.2	129.1	4.0	9.1	
E top	1565	161.1	128.3	4.0	10.8	
F top	1566	125.1	120.8	1.0	3.2	DISCARDED (2)
G top	1567	164.1	135.4	4.0	9.2	
J bot.	1568	161.2	131.1	4.5	12.2	
L top	1569	162.9	135.4	4.0	10.8	
				10-25-82		
H bot.	1571	161.7	128.7	4.0	9.2	
I bot.	1572	155.7	125.8	4.0	9.0	
K bot.	1573	160.0	130.8	4.5	12.5	
L bot.	1574	154.2	130.4	4.0	10.8	
				10-26-82		
Combined Results	X	159.0	129.1	4.0	10.3	
	N	22	21	21	21	
	S	2.78	3.05	0.25	1.36	
Top Only	X	160.0	129.7			
	S	10	10			
	N	2.39	3.98			
Bottom Only	X	158.1	128.6			
	S	12	11			
	N	2.88	1.96			
Design	A	150.0	119.1	3.18	5.86	
	B	153.8	123.3	3.52	7.71	
t ratio		1.66	0.82			
Sig. Difference		NO	NO			

(1) Bond interface in threads
(2) Damaged in machining. Failed remote from bond.

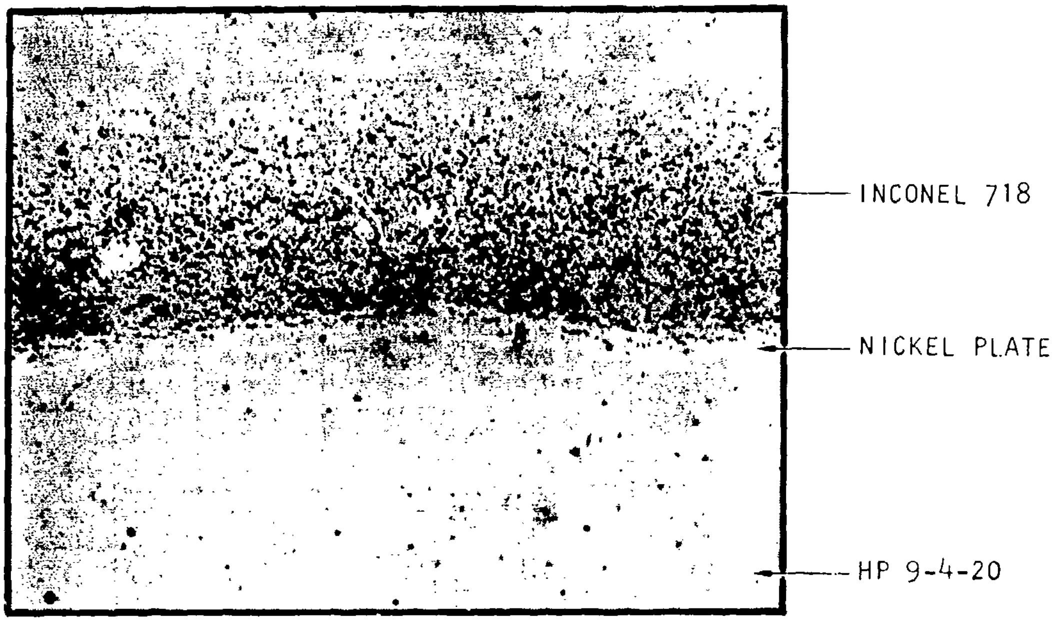


Figure 3A-1. Hot Isostatic Pressure Bond. No Porosity Evident. Bond Is Excellent. Unetched, Magnified 100X.

F-38186

Figure 3A-2. Hot Isostatic Bond. No Porosity Evident. Bond Is Excellent. Etched in 4-Percent Nital, Magnified 100X.

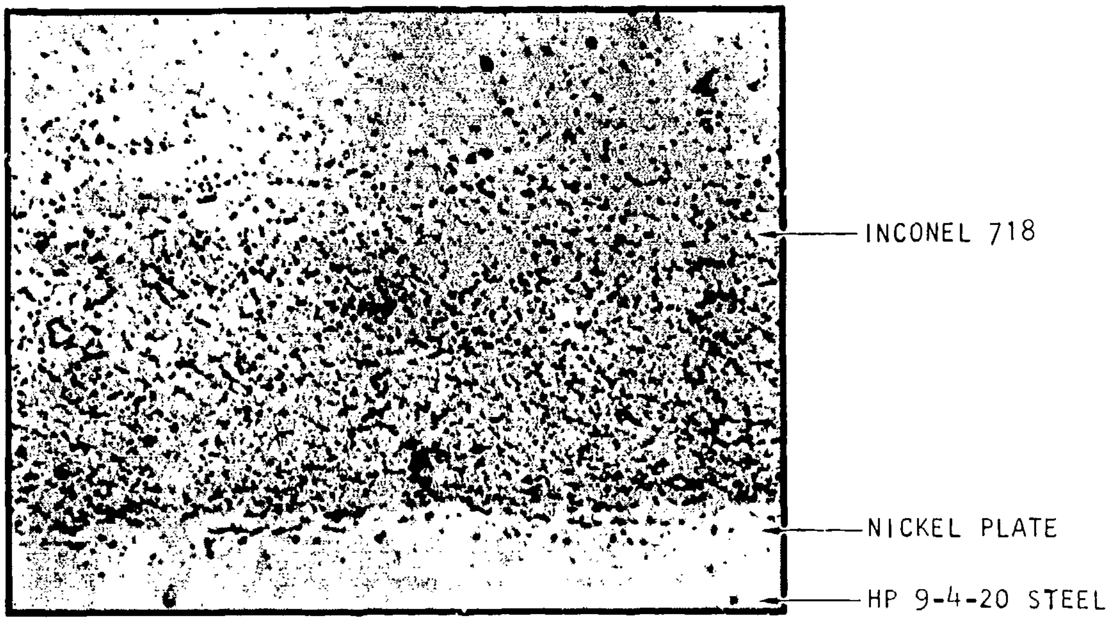
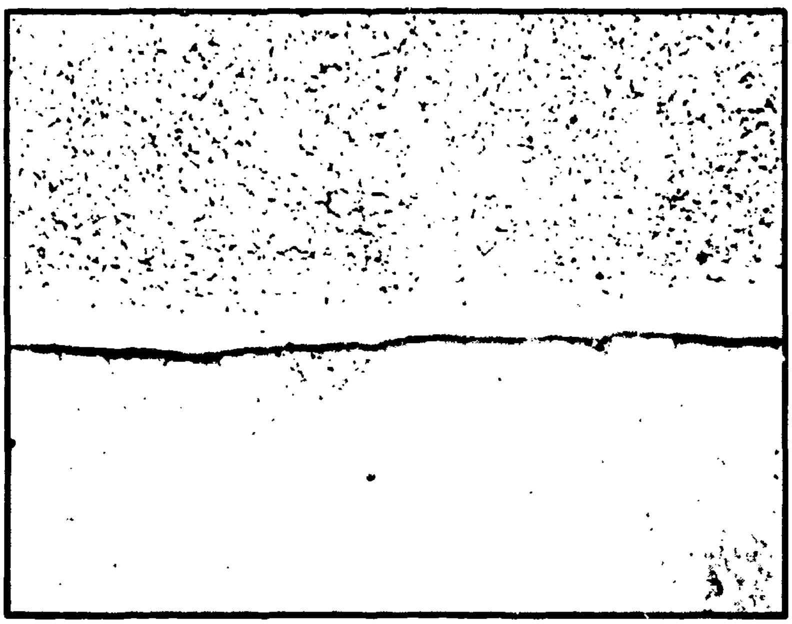


Figure 3A-3. Carbides in the Inconel Are Well Broken Up. No Continuous Networks as in Previous Bonds. Unetched. Magnified 225X.



F 38185

Figure 3A-4. Carbides in the Inconel Are Well Broken Up. No Continuous Networks as in Previous Bonds. Unetched. Magnified 225X.

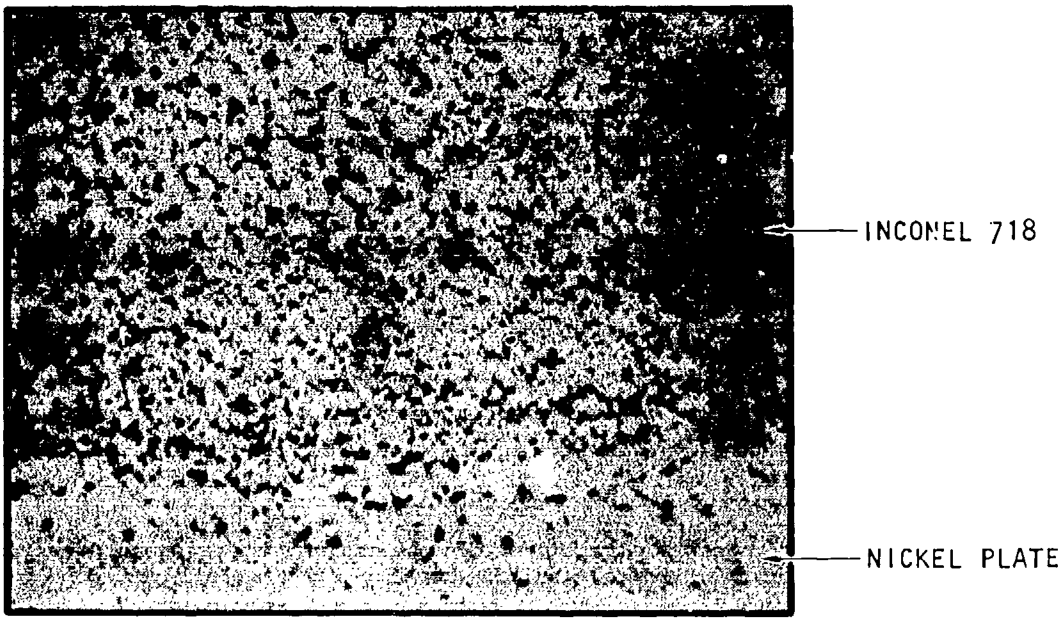
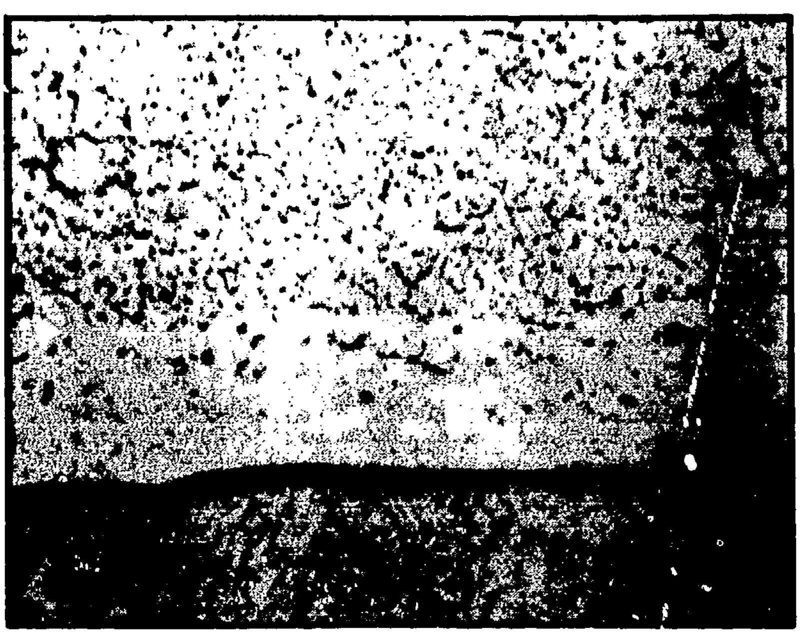


Figure 3A-5. Carbides Are Well Spheroidized. Unetched. Magnified 500X.



F-38184

Figure 3A-6. Carbides Are Well Spheroidized. Etched in 4-Percent Nital. Magnified 500X.

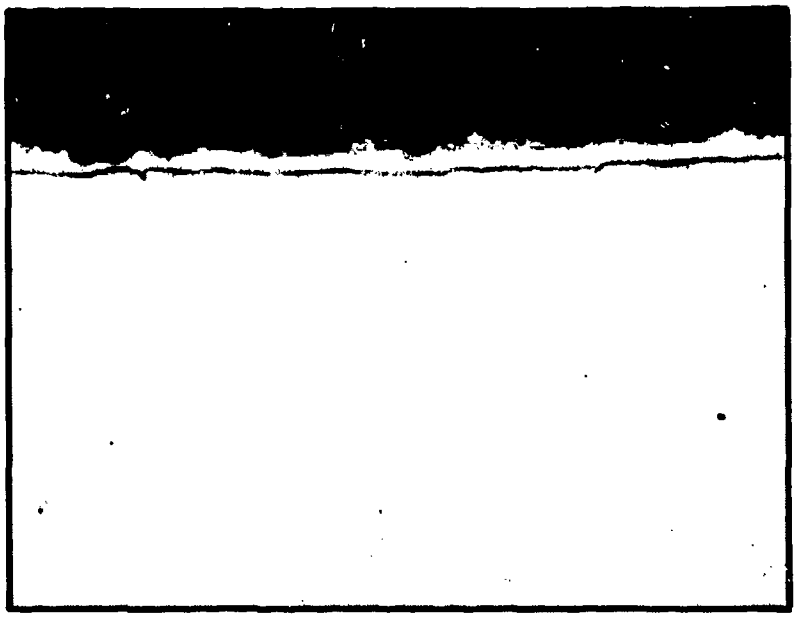


Figure 3A-7. Typical Tensile Rupture. Etched in 4-Percent Nital. Magnified 100X.

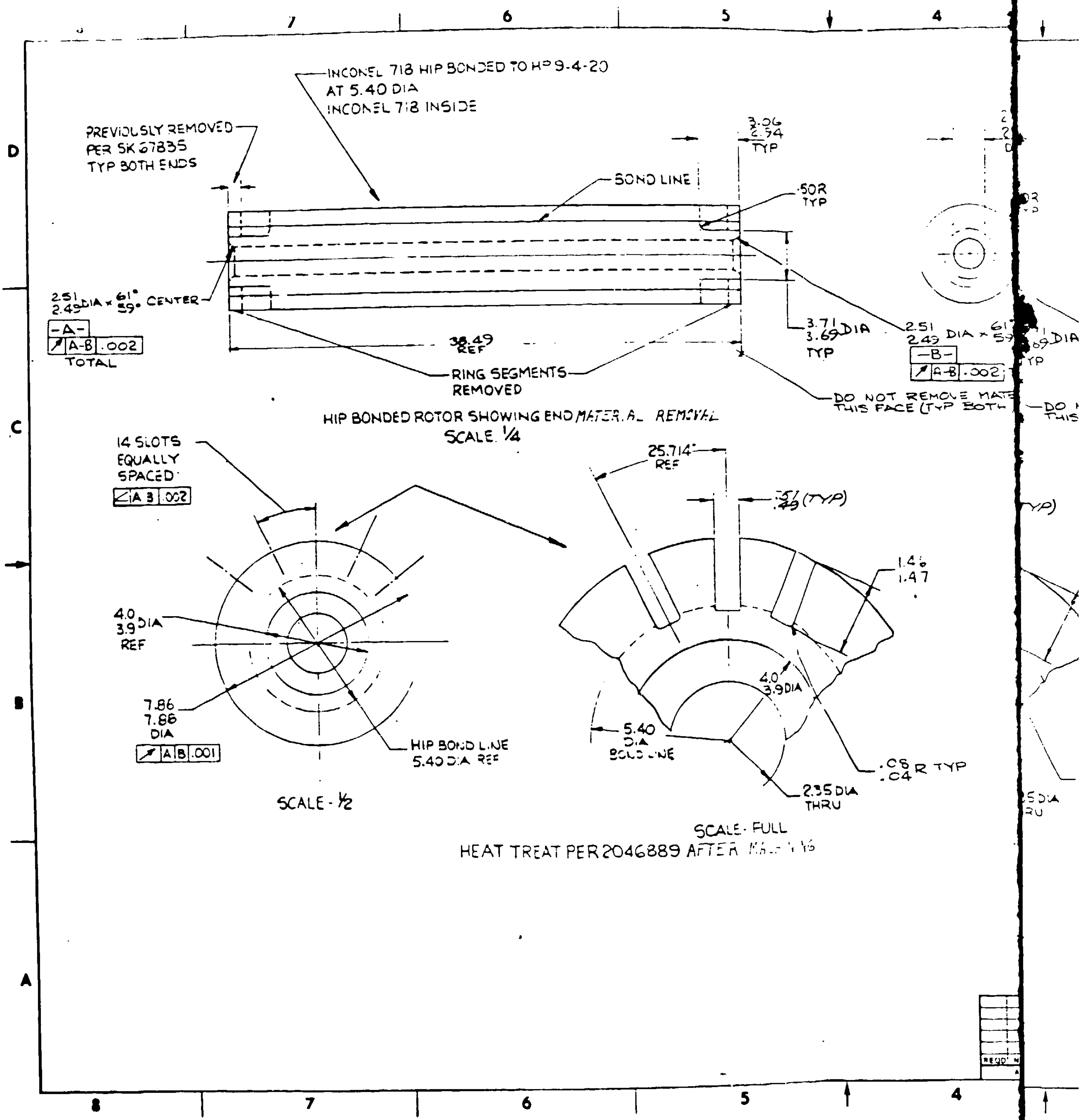
F-38187

Figure 3A-8. Typical Tensile Rupture. Failure Occurred within Inconel 718 Carbide Precipitation Zone. Magnified 225X.

4. HEAT TREAT

The outside diameter, end stubs, lightening holes, and heat-treat slots were scheduled for machining prior to heat treat. Lightening starter holes were predrilled at F.D. Contours and completed at Thompson Gun Drilling Co. Difficulties were encountered in drilling the 1/2-x-32-in.-holes 16 in. from each end because the drill tends to move off center. Alternates to gun drilling, such as EDM or chemical milling, were considered too developmental and costly for this program. After careful examination of all the tradeoffs involved and discussions with the Air Force, the lightening holes were eliminated.

The rotor was slotted as shown on Figure 4-1, with the slot width increased to 1/2 in. for removal of the starter lightening holes. Originally the slots were to be 0.060 in. wide and located between the lightening holes. The slots prevent buildup of radial stresses due to differential thermal expansion of the two rotor materials during the heat treatment cycle. Heat treatment was performed to the specifications of Figure 4A-1, Exhibit 4A. See Figures 4-2 and 4-3. Certification of the heat-treat process is shown in Figure 4-3. The AiResearch materials engineering report is shown in Exhibit 4B.



GARRETT AIRESEARCH MANUFACTURING COMPANY

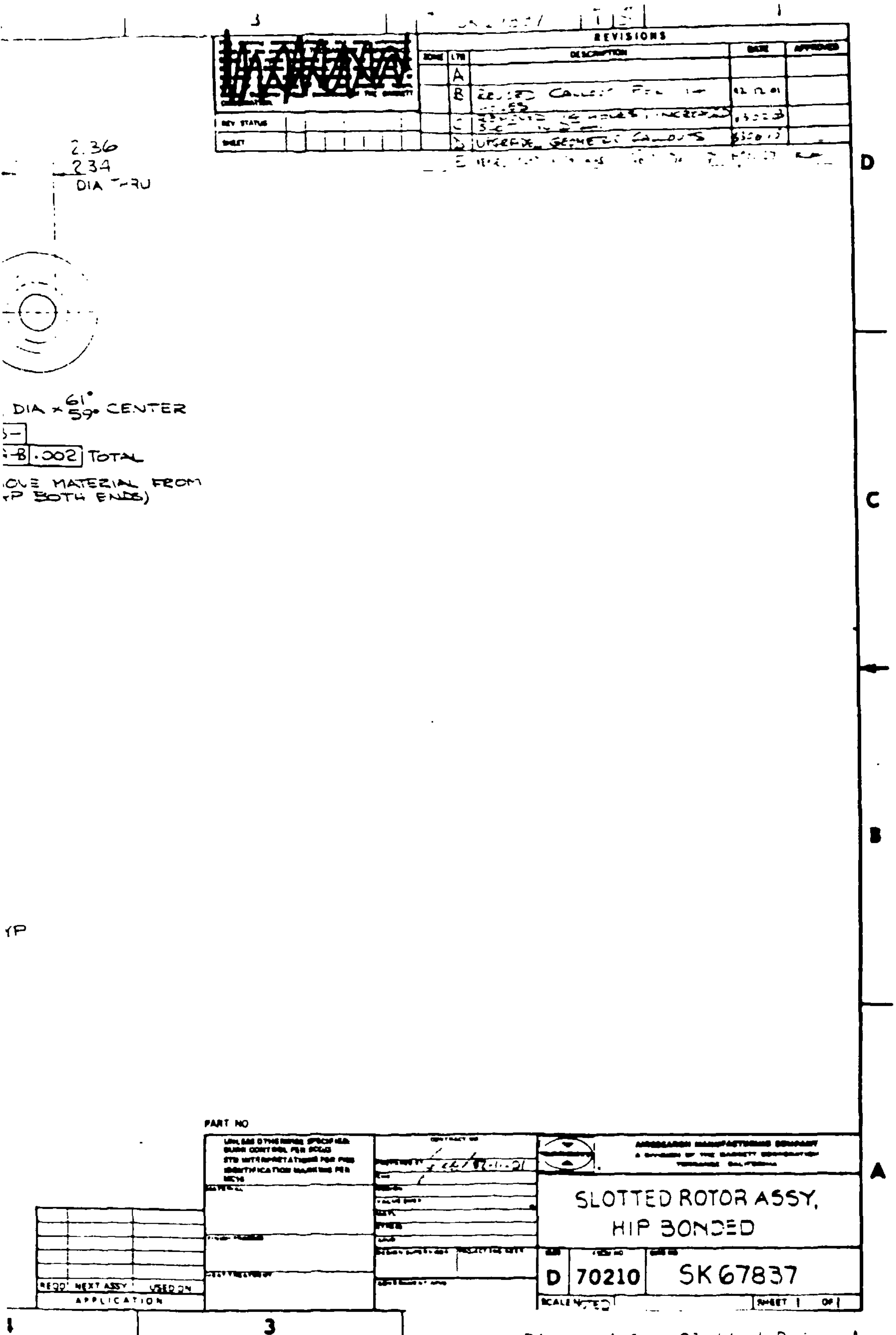


Figure 4-1. Slotted Rotor Assembly, HIP-Bonded

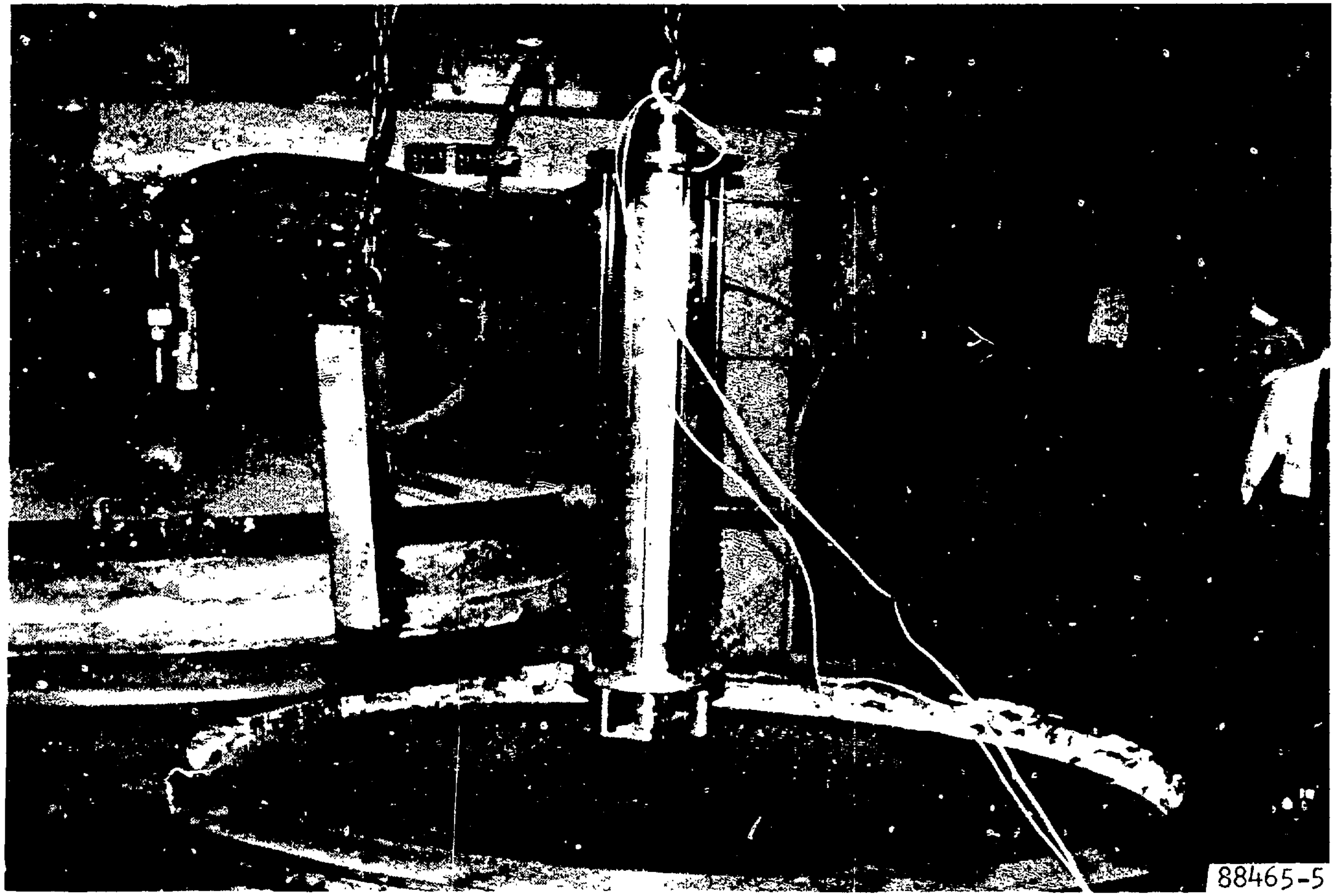


Figure 4-2. Rotor Entering IST Heat Treatment Furnace

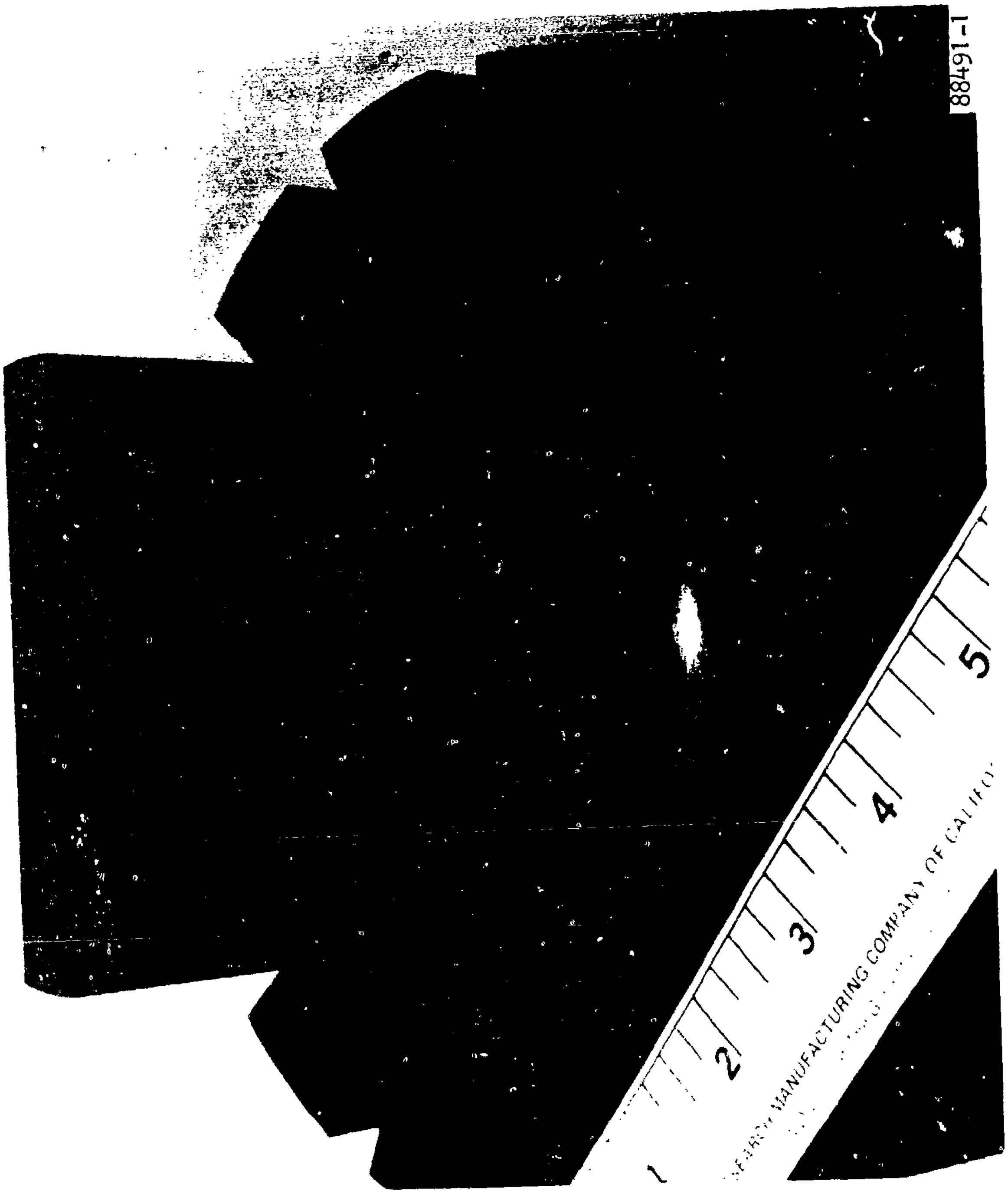


Figure 4-3. Closeup of Rotor After Heat Treatment

K-10467

FORM NO. 6.0 1 ST.

CERTIFICATION OF PROCESS

INDUSTRIAL STEEL TREATING COMPANY - 3370 BENEDICT WAY - HUNTINGTON PARK, CALIFORNIA

CUSTOMER: AIRESEARCH MFG	PROCESS NO.: 338926
CUST. P.O. NO.: 694-673196-3 · CUSTOMER'S SHIPPER NO.: · SAMPLES REQUIRED: ☐ YES ☐ NO · SIZE:	DATE RECEIVED: 7/12/83
QUANTITY: 1 · DESCRIPTION: ROTOR P/N 2046856-1 · PART NO.:	MATERIAL: HP9-4-20 & INCONEL · CONDITION: 718
PASSIVATION BEFORE: AFTER: · MAX. SECT.: · REQUIRED HARDNESS: INCONEL RC 35 MIN; HP 9-4-20 RC 38 MIN	WEIGHT EA.: TOTAL:
HEAT TREAT	% INSPECTION: 8 TEST PCS · CASE: · CORE:
WE CERTIFY THAT THE ABOVE DESCRIBED PARTS WERE PROCESSED IN ACCORDANCE WITH SPECIFICATION NOS. PER PROCEDURE & INST.	FINAL INSPECTION BY: INCONEL RC 35/36; ~~HP 9-4-20 RC 38/39~~

THE FOLLOWING READINGS AND CASE DEPTH WERE OBTAINED IF APPLICABLE

	REQUIRED	LAB RESULTS	METHOD
CASE HDNS.			
CORE HDNS.			
CASE DEPTH			
CARBON %			

SIGNED

EQUIP. NO.	LOAD NO.	PROCESS	TEMP.	DATE	TIME IN	TIME OUT	HRS. AT H.T.	ATMOS.	DEW PT.	QUENCH MEDIUM
6H	1	SOL	1750	7/18	1:35	T/C time 8:15 p.m.	1 HR	ARGON		SEE ATTACHED SHEET
6H	1	ANNEAL	1400	7/18	9:15pm	6:15 am	5 HRS	ARGON		
6H	1	ANNEAL	1200	7/18	9:25am	10:25 am	1 HR	ARGON		
6H	1	COOL TO 700F			10:25 am	3:00 pm		ARGON		
S-Z	1	COLD STAB	-100	7/20	9:00am	3:45pm	4 HRS			
6H	1	AGE	1000	7/20	6:30pm	1:30 am	4 HRS	ARGON		
S-Z	1	COLD STAB	-100	7/21	9:30am	4:05pm	4 HRS			
6H	1	AGE	1000	7/21	10:10pm	2:30am	4 HRS	ARGON		

ADDITIONAL

SIGNED Sharon Hampton

IST. 2 ASST. MGR.

Figure 4-4. Certification of Heat-Treat Process

EXHIBIT 4A

HEAT-TREATMENT PROCEDURE

~~This drawing contains designs and other information which are the property of the GARRETT CORPORATION. Except for rights expressly granted to the United States Government, this drawing may not in whole or in part be duplicated or disclosed or used for manufacture of the part disclosed herein, without the prior written permission of the GARRETT CORPORATION.~~

APPLICATION		REVISIONS			
NEXT ASSY	USED ON	LTR	DESCRIPTION	DATE	APPROVAL
2046856-1	2046870	A	SEE E.O.	82 10 19	Withan

1. This drawing describes the heat treatment of 2046856-1 rotor after undergoing Hot Isostatic Press (HIP) bonding
2. Shafts are made from Inconel 718 ref. and sleeves are HP 9-4-20 Ref.
3. Heat treatment is similar to AF642 without solution anneal. However, the cooling rates in the HIP cycle should provide an adequate solution anneal.

Notes: Unless otherwise specified

SHEET INDEX			
	REVISION LTR	A	A
	SHEET NO	1	2

CONTRACT NO		AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA A DIVISION OF THE GARRETT CORPORATION TORRANCE, CALIFORNIA
DFT C DUNMIRE	780509	
CHK	5-9-78	HEAT TREATMENT, ROTOR
APPD	4-9-79	
APPD	4-9-79	
AIRESEARCH APPD	4-16-79	SIZE A
OTHER ACTIVITY APPD		CODE IDENT NO 70210
		DWG NO 2046889
		SCALE
		SHEET 1 OF 2

FORM 8847-8 (1-74)

Figure 4A-1. Heat Treatment, Rotor

4. Heat treat is as follows:

   a) Heat in vacuum or inert atmosphere to 1750°F ± 25°F at a rate not exceeding 25°F per minute. After temperature stabilizes, hold at 1750 ± 25°F for one hour.

   b) Cool to 1400°F in inert atmosphere or vacuum using a cooling rate of 100°F per hour.

   c) Hold at 1400°F ± 20°F for 5 hours.

   d) Furnace cool from 1400°F to 1200°F ± 20°F at a rate of 100°F per hour.

   e) Hold at 1200°F ± 20°F for 1 hour.

   f) Air cool to room temperature, avoiding non-uniform cooling. Protect from drafts, do not fan cool.

   g) Cool to -100° ± 10°F at a rate not greater than 25°F per minute.

   h) Hold at -100° ± 10°F for 4 hours.

   i) Heat to 1000° ± 30°F at a rate not greater than 25°F per minute.

   j) Maintain at 1000° ± 30°F for 4 hours.

   k) Air cool to room temperature, avoiding non-uniform cooling. Do not fan cool.

   l) Repeat steps g through k.

5. Rotors processed per Note 4 will have hardness of

Inconel 718	40 HRC MIN
HP 9-4-20	37 HRC MIN

AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA A DIVISION OF THE GARRETT CORPORATION TORRANCE, CALIFORNIA	SIZE A	CODE IDENT NO 70210	DWG NO 2046889
	SCALE	REV A	SHEET 2 OF 2

FORM 2347-4 (1-74)

Figure 4A-1. (Continued)

EXHIBIT 4B

METALLURGICAL REPORT

HEAT TREATMENT OF
HIP-BONDED
9-4-20 STEEL-INCONEL 718 ROTOR

HEAT TREATMENT OF HIP BONDED 9-4-20 STEEL - INCO. 718 ROTOR

Heat treatment of the subject part was accomplished in an argon furnace at Industrial Steel Treating of Huntington Park, California in accordance with the schedule specified in Figure 4A-1. Unexpectedly a leak in the furnace developed and resulted in decarburization, the depth of which was 0.015 inch, Figure 4B-1. The decarburized layer in the rotor was subsequently removed during the final machining operation.

The hardness values were 43 HRC for 9-4-20 steel and 38 HRC for INCO. 718 and satisfied the requirements of Figure 4A-1.

Tensile properties were determined from three HIP bonded 9-4-20 steel - INCO. 718 specimens per SK 34074 with the bond zone at the center of the test section. These specimens were fabricated from a disc segment that accompanied the rotor throughout its thermal processing. As can be seen in Table 4B-1, the results were comparable to the properties developed during the experimental development stage (Specimen J). Tensile rupture occurred at the bond on the INCO. 718 side.

Metallographic examination revealed that the microstructure was normal for both 9-4-20 steel and INCO. 718. The bonded diffusion zone was characterized by fine carbides uniformly distributed in the INCO. 718 matrix, Figure 4B-2.

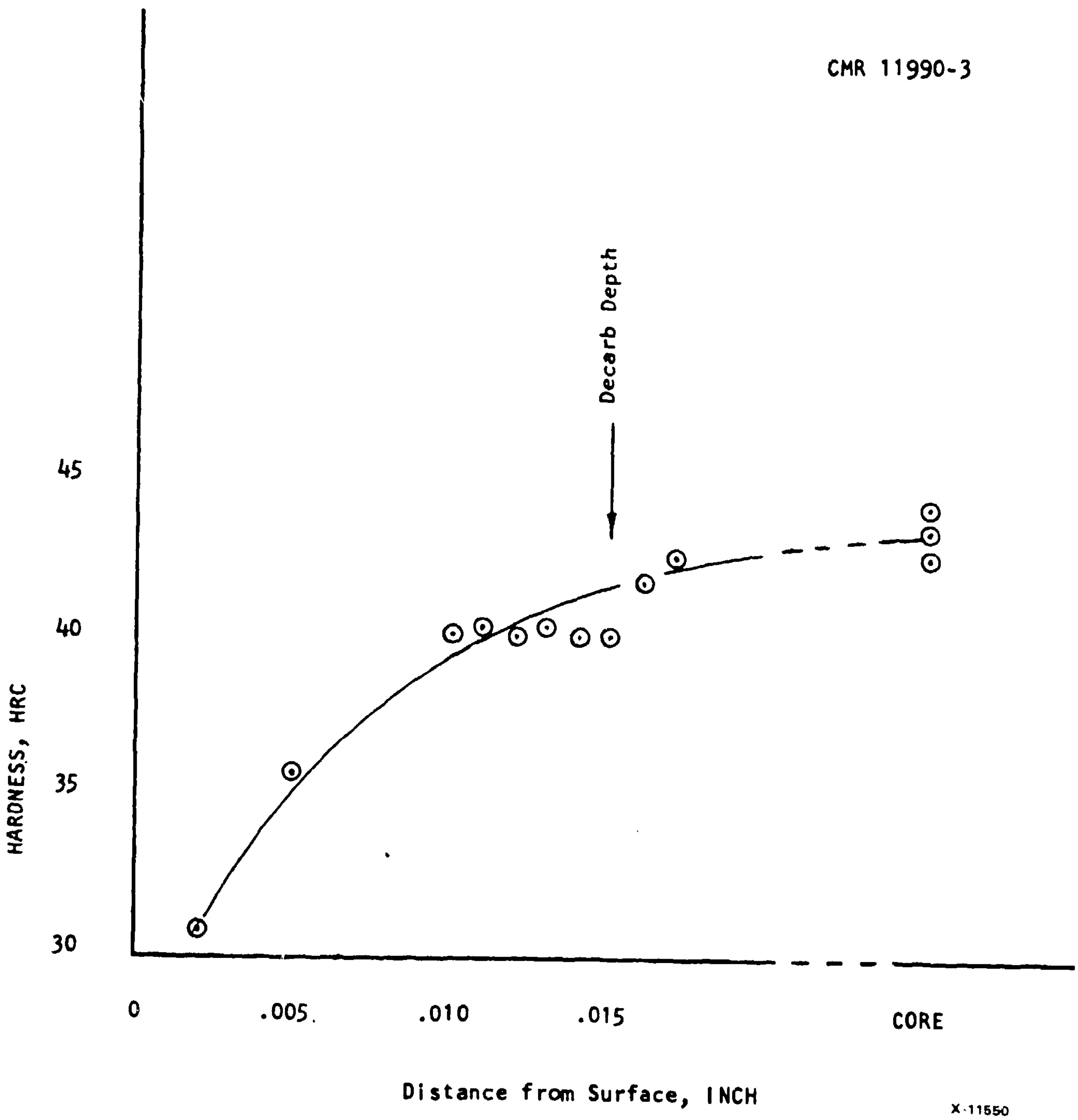


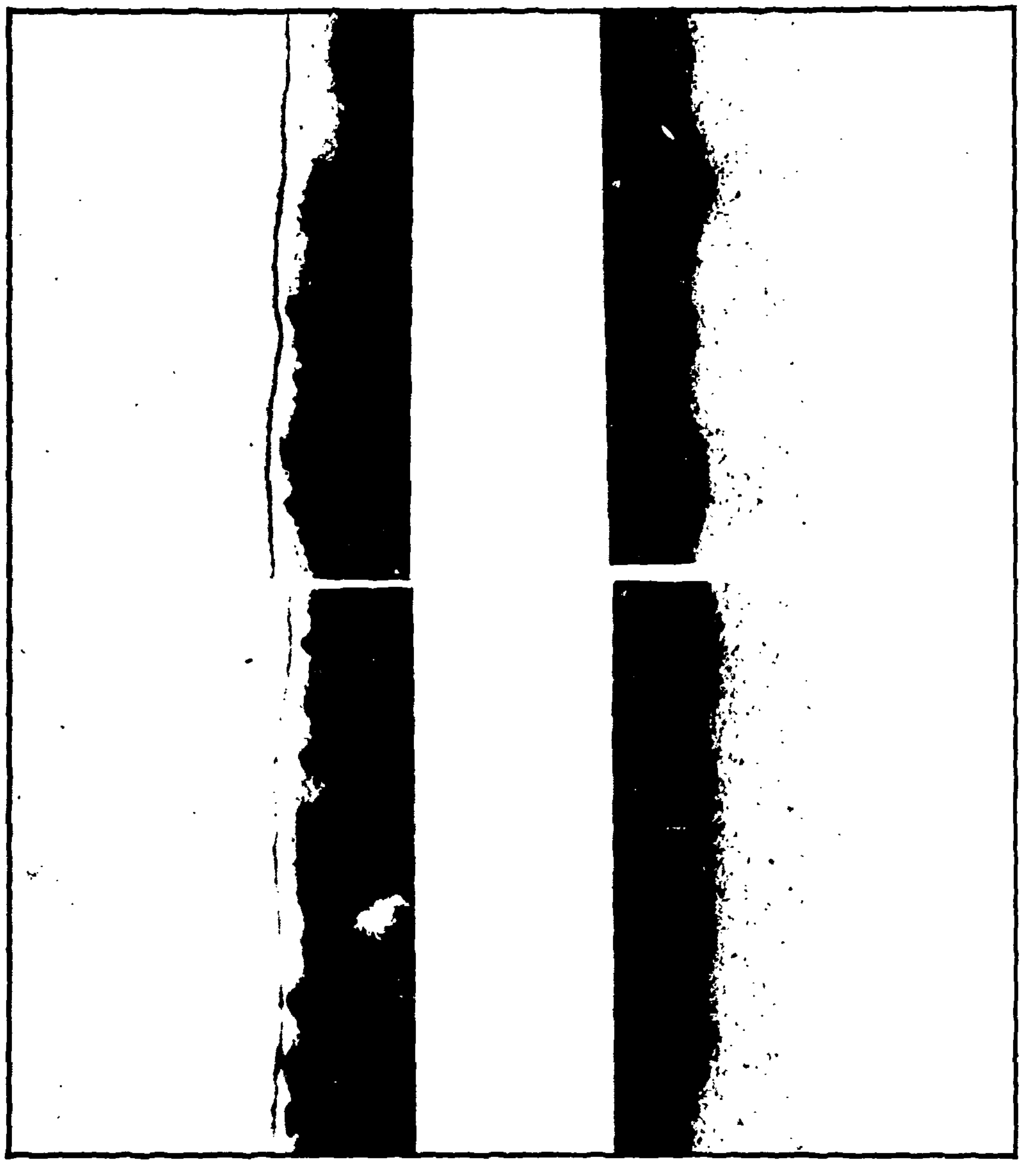
Figure 4B-1. Decarburization Curve for 9-4-20 Steel Rotor

TABLE 4B-1

TENSILE PROPERTIES OF 9-4-20 STEEL-
INCO. 718 HIP-BONDED SPECIMENS

SPECIMEN	DESCRIPTION	FTU, KSI	FTY, KSI	% ELONG
1	Heat treated at AiResearch (Sept., 1982 and then heat treated with the part at Industrial Steel Treating on 7-18-83 for heat treat verification.	151.1	133.3	2.0
2		160.7	132.0	2.4
3		155.9	141.9	3.6
Average of 1, 2, 3		155.9	135.7	2.7
J	As heat treated at AiResearch (Sept., 1982)	159.0	130.1	3.4
Design values*	"A"	150.0	119.1	3.2
	"B"	153.8	123.3	3.5

*"A" and "B" basis design minimums reported in CMR (No number) dated 11-1-82



9-4-20 STEEL　　TENSILE DIRECTION　　INCO 718　　F 41661

Figure 4B-2. Photomicrographs Showing Tensile Rupture at the Bond on the 718 Side. Note the Uniform Distribution of Fine Carbides in 718. 9-4-20 Steel Shows Tempered Martensite. (100X)
TOP ROW: Specimen 3　　BOTTOM ROW: Specimen J
Refer to Table 1 for test data.

5. ROTOR MACHINING

The rotor was machined at F.D. Contours in Irvine, California, where the owner, Stu Folger, personally oversaw the work.

The work included the following steps:

(a) Rough mill rectangular slots before heat treatment

(b) Machine bottom of slots to final dimension

(c) Machine slot sides to within 0.020 in. of final dimension

(d) Machine slot sides to within 0.003 in. of final dimension

(e) Grind slot sides to final dimension

The rotor was rough machined with carbide end mills on a Bostomatic milling machine with the rotor mounted on an indexing head (see Figure 5-1).

Final sizing of the slots was performed with a special form Borazon grinding wheel (see Figure 5-2) mounted on the Bostomatic. Grinding of the slots to final dimensions was more time-consuming than originally anticipated, due to rapid wearing of the wheel and excessive vibration at high speeds and feeds. Three wheels were required to finish the slots. The F.D. Contours setup for grinding the slots on the Bostomatic is shown in Figure 5-3.

The slot size was measured at the vendor using three independent methods:

(a) A taper gage was fabricated to inspect the rotor slot width at the tooling point dimensions. The taper gage was constructed with a pad from which to measure the relative deviation between slots. Measured heights varied a total of 0.006 in., resulting in a width deviation between slots of less than 0.001 in.

(b) A dummy magnet with a 0.009-in. shim on each side was inserted into the slot. The height of the dummy magnet was checked relative to the outer diameter of the poles. Readings ranged from 0.007 in. to 0.021 in. below the rotor outside diameter. It was necessary to move the dummy magnet from the slot to measure the height; thus, the accuracy of these measurements may vary.

(c) The angle of the slot was measured using a sine plate. The included angle varied from +6 to -2 arc seconds of angle, well within drawing requirements.

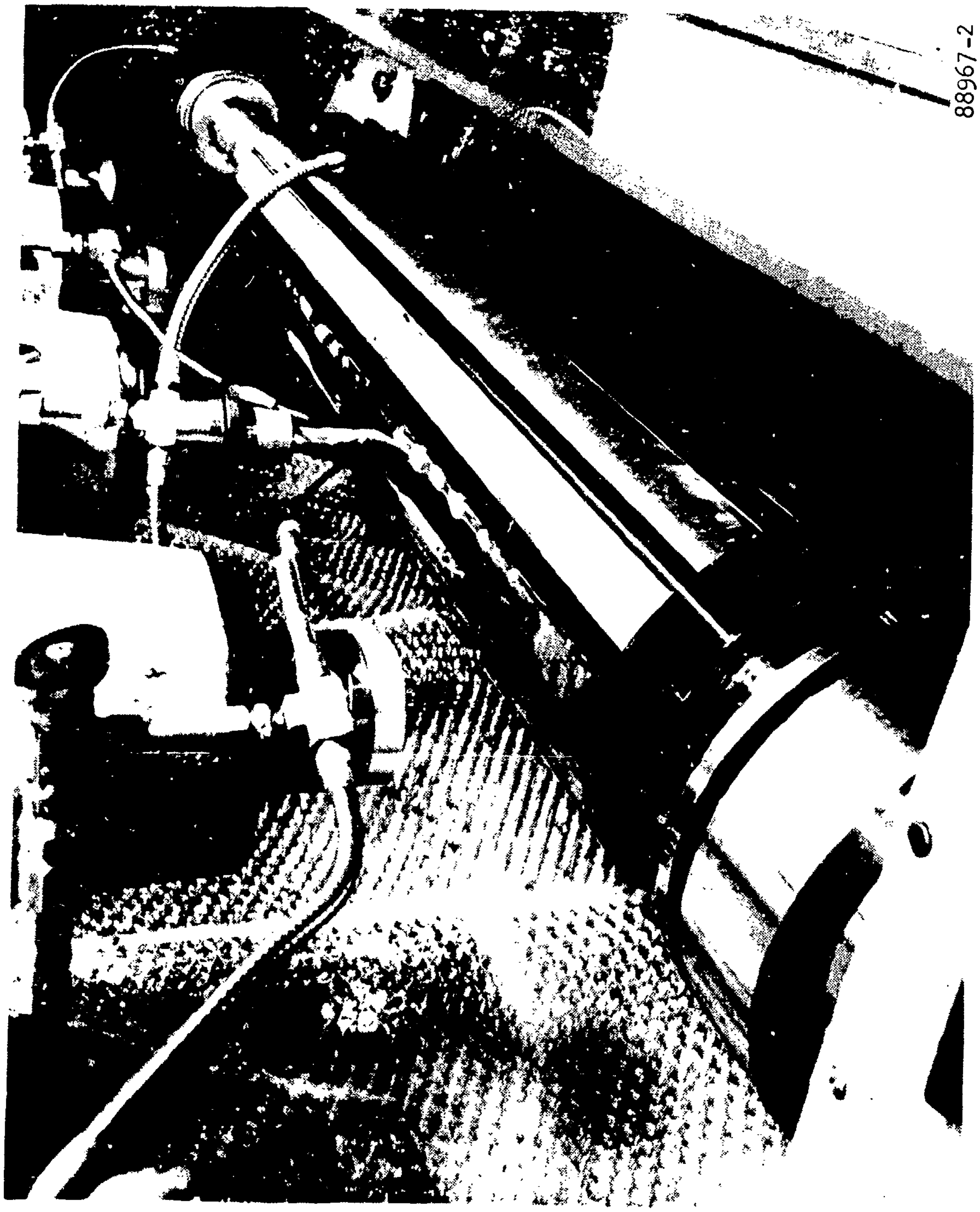


Figure 5-1. Rough Cutting Slots on Bosto-Matic Mill

K-10468

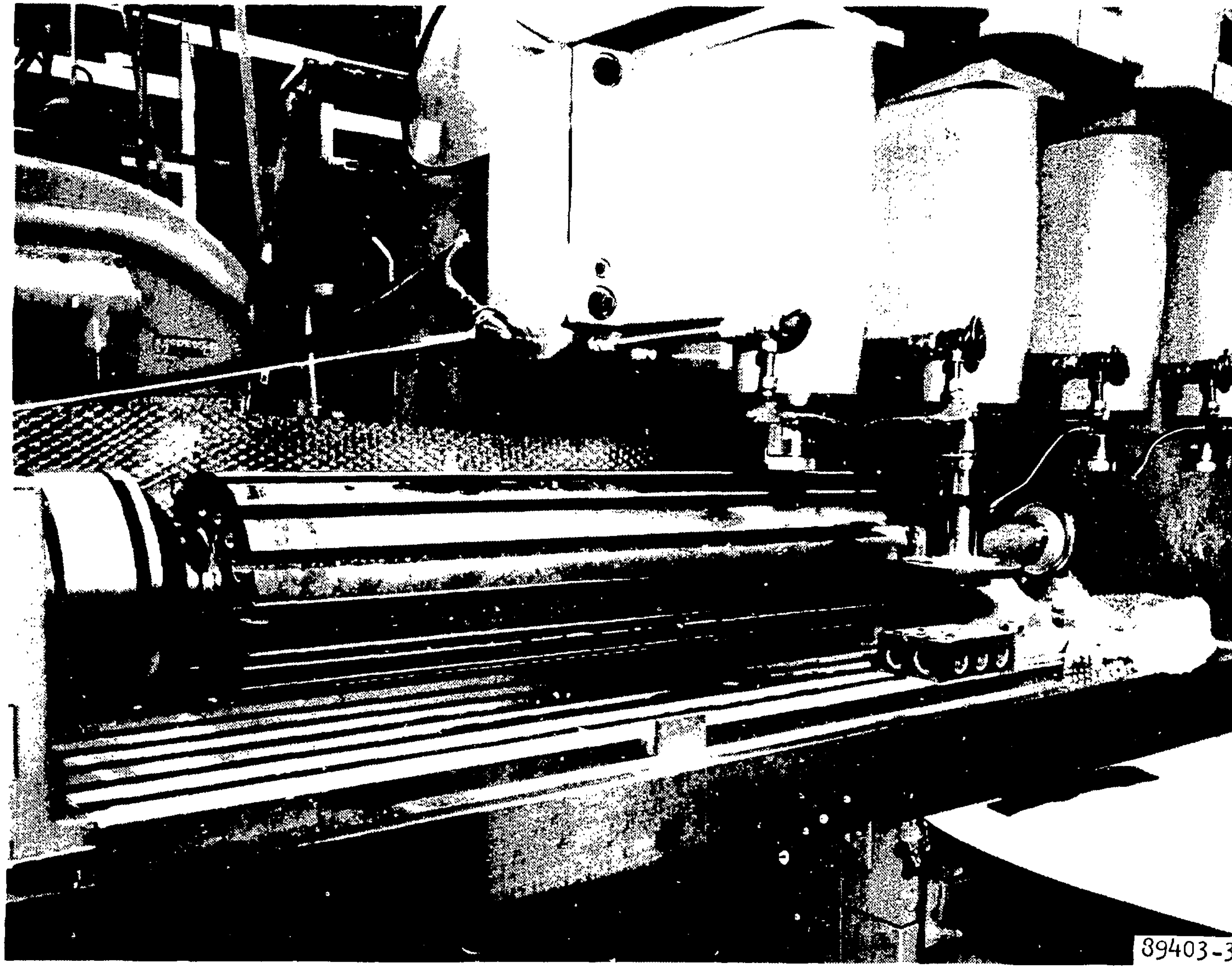


Figure 5-2. Final Grinding Slots with Borazon Grind Wheel

K-10469

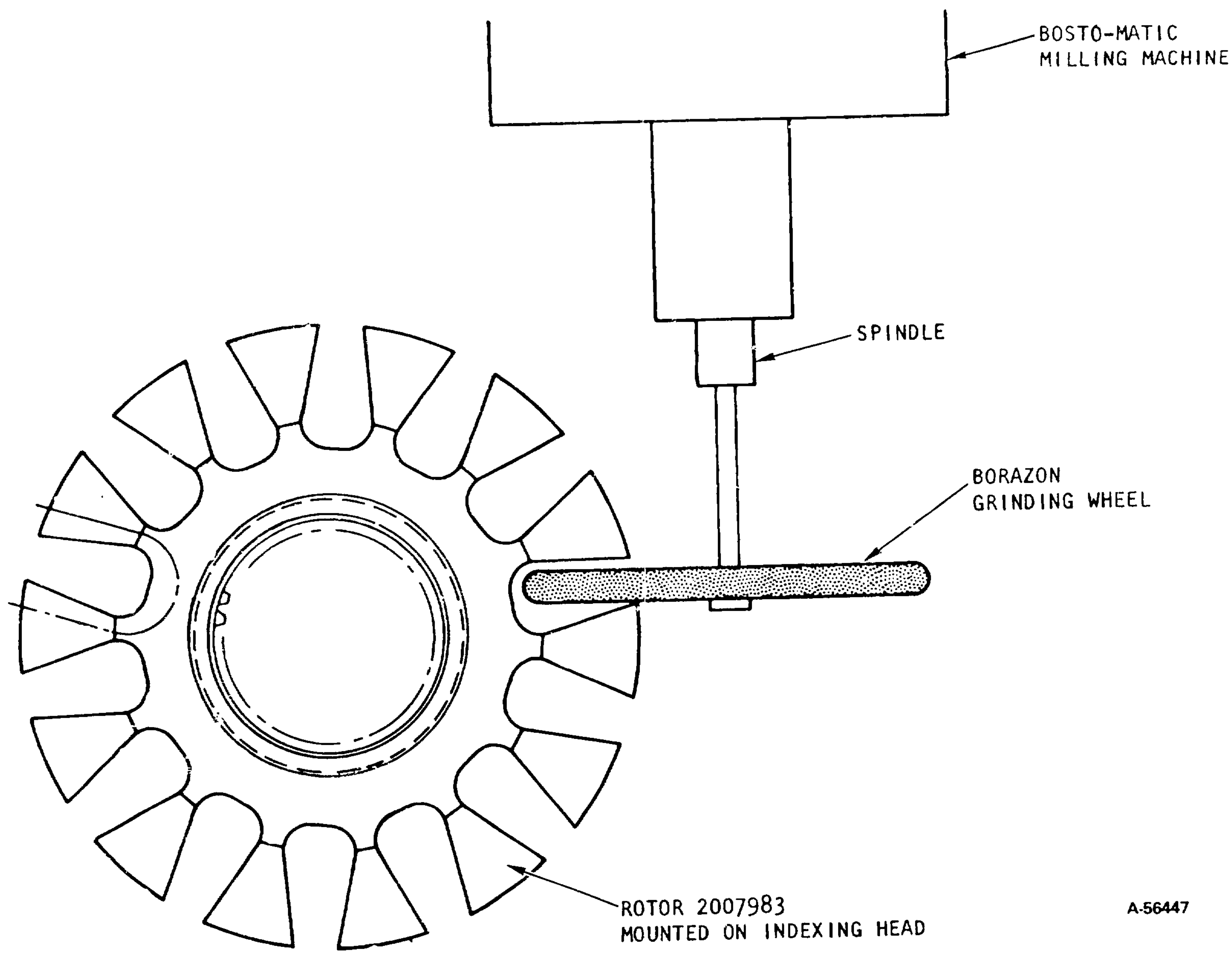


Figure 5-3. Slot Grinding Setup

A flat spot was discovered on the No. 1 slot during inspection (see Figure 5-4. No action was taken other than a check for magnet cracking during each spinup.

The internal spline was cut at Advance Gear and Machine Corporation. A test cut was made on a sample of Inconel 718 as shown in Figure 5-5. The test sample was considered necessary due to the expense (both time and money) of the rotor and the no-room-for-error policy guiding the program. Several photographs of the gear cutting process are included in Figures 5-6 through 5-8.

Final inspection of the rotor was performed at the AiResearch Western Avenue facility. The rotor was mounted on a 36-in. precision rotary table and moved into position with one slot parallel to the surface plate and the position recorded within 2 arc sec. The rotor was then moved to place the opposite side of the slot in a position parallel to the surface plate and record the angular position. The difference between the two positions is equal to the slot angle. All measurements were taken at the midpoint of the rotor. Results are displayed in Table 5-1. Also see Figure 5-9.

Fluorescent penetrant inspection was used to examine the rotor for discontinuities at the HIP bond interface. There were none.

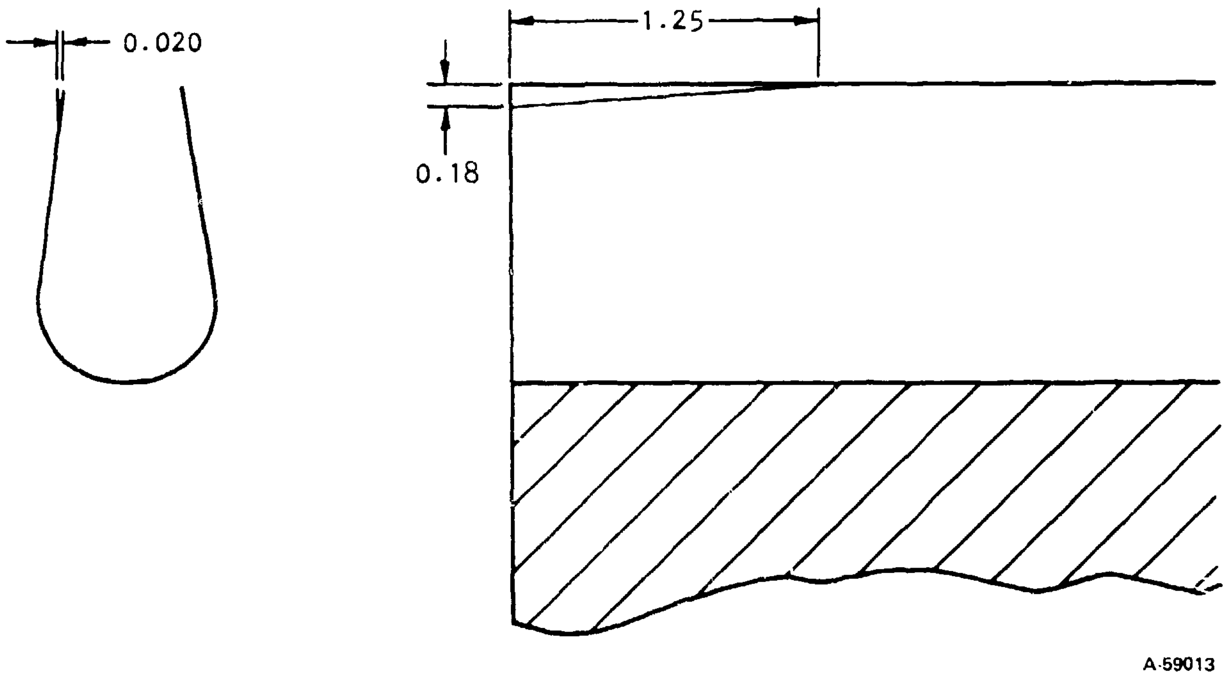


Figure 5-4. Flat Spot on Slot 1

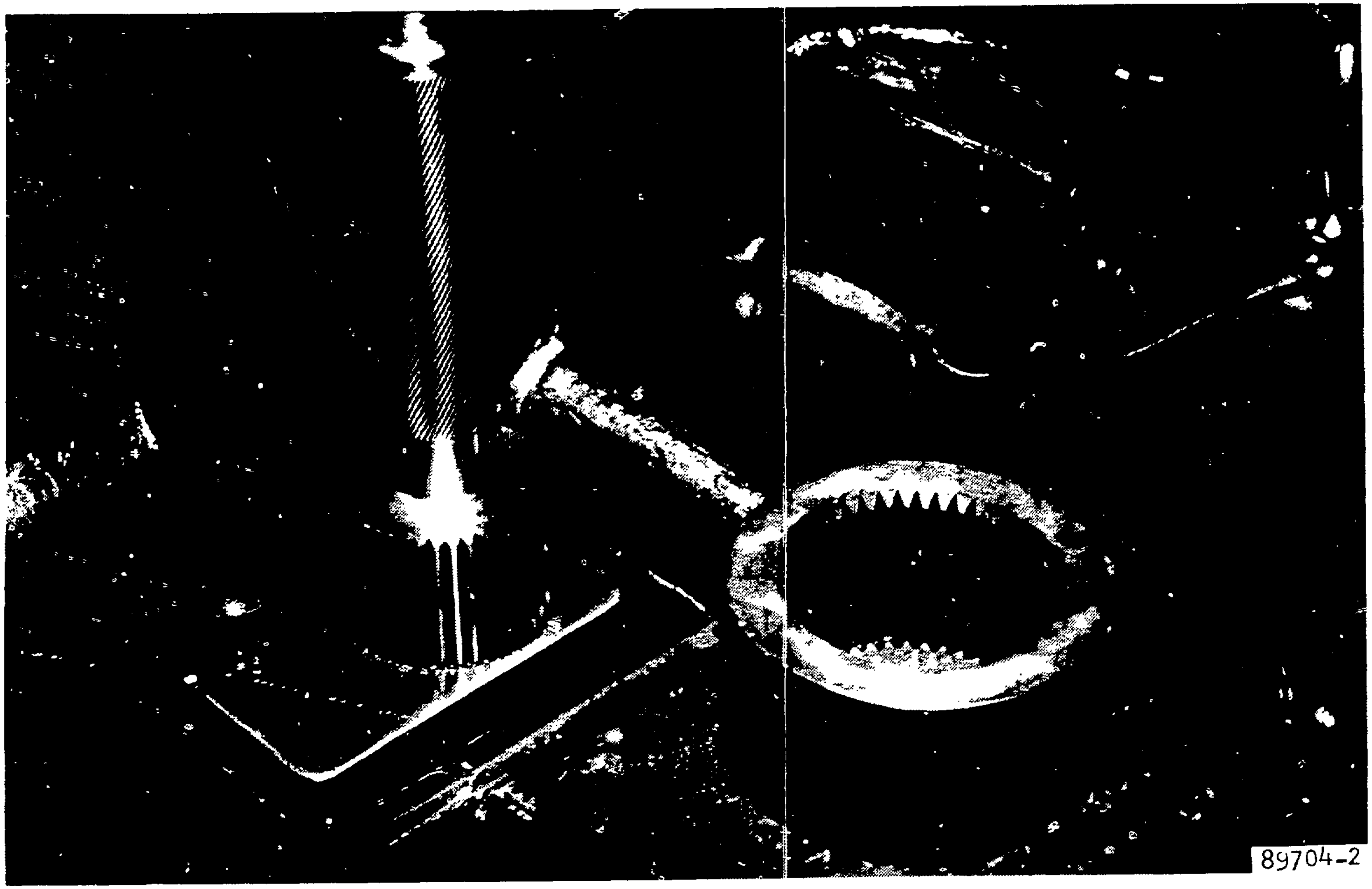


Figure 5-5. Inconel 718 Test Sample and Spline Gage

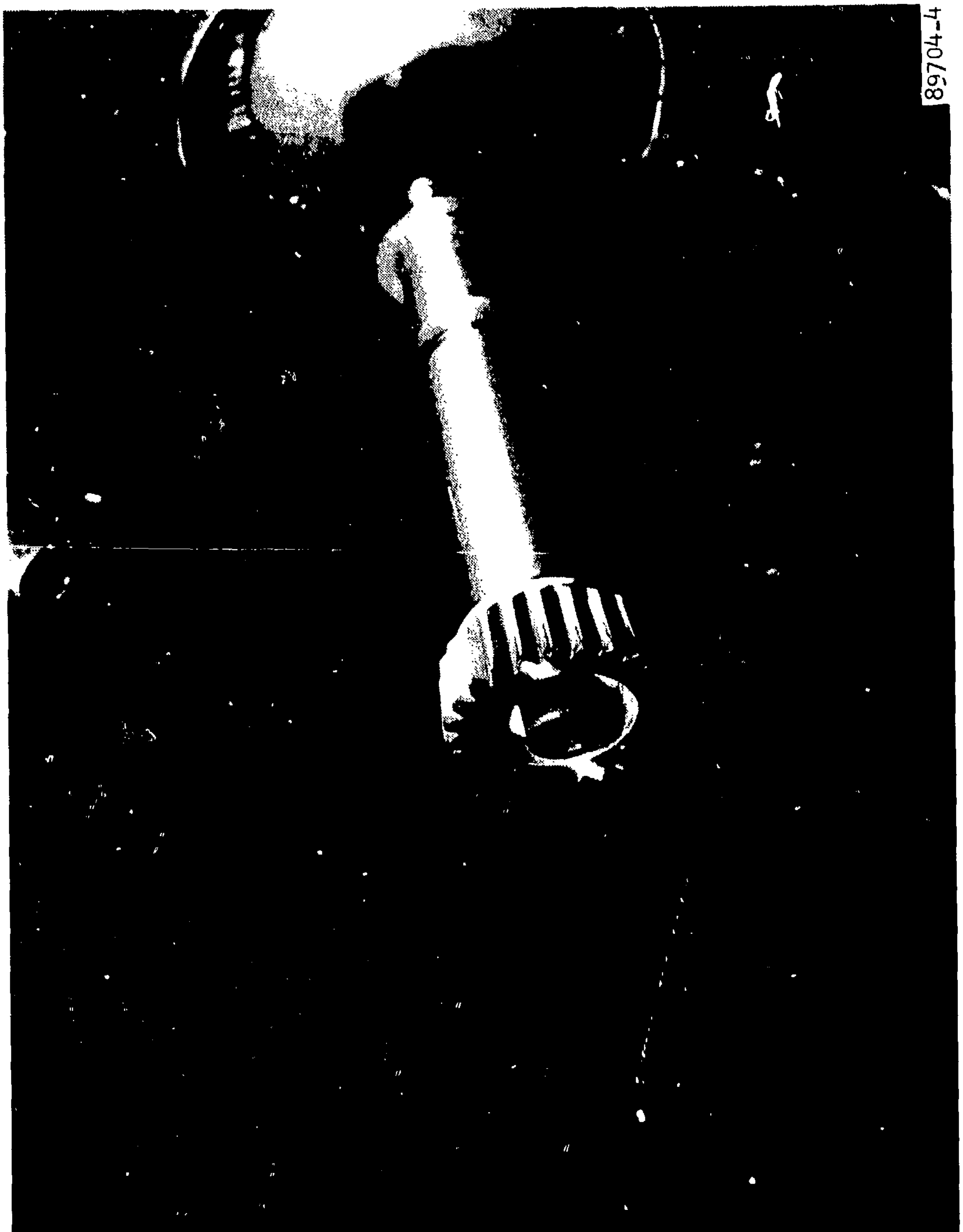


Figure 5-6. Cutting Tool

K-10471

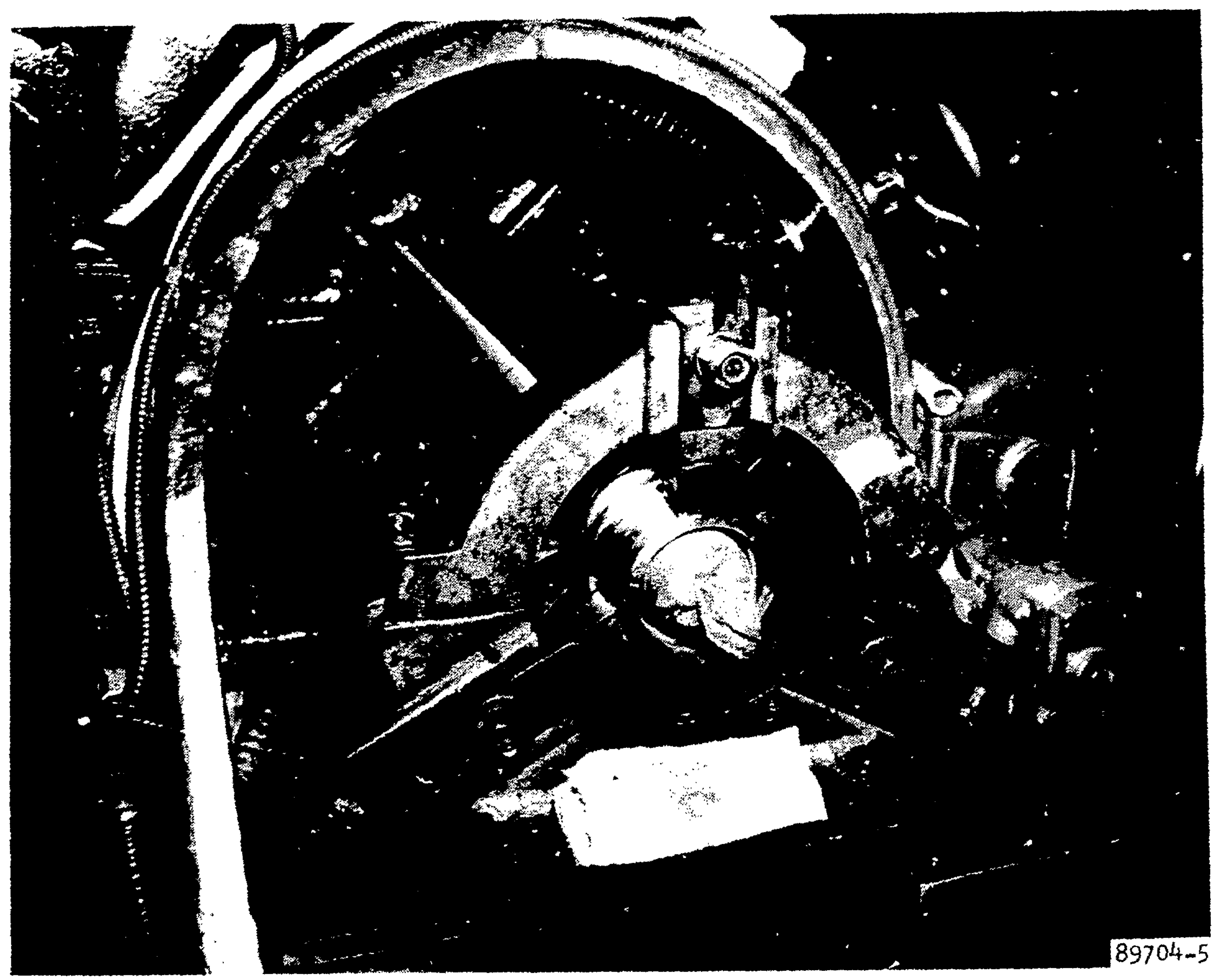


Figure 5-7. Rotor-Holding Fixture Opposite Spline End

K-10472

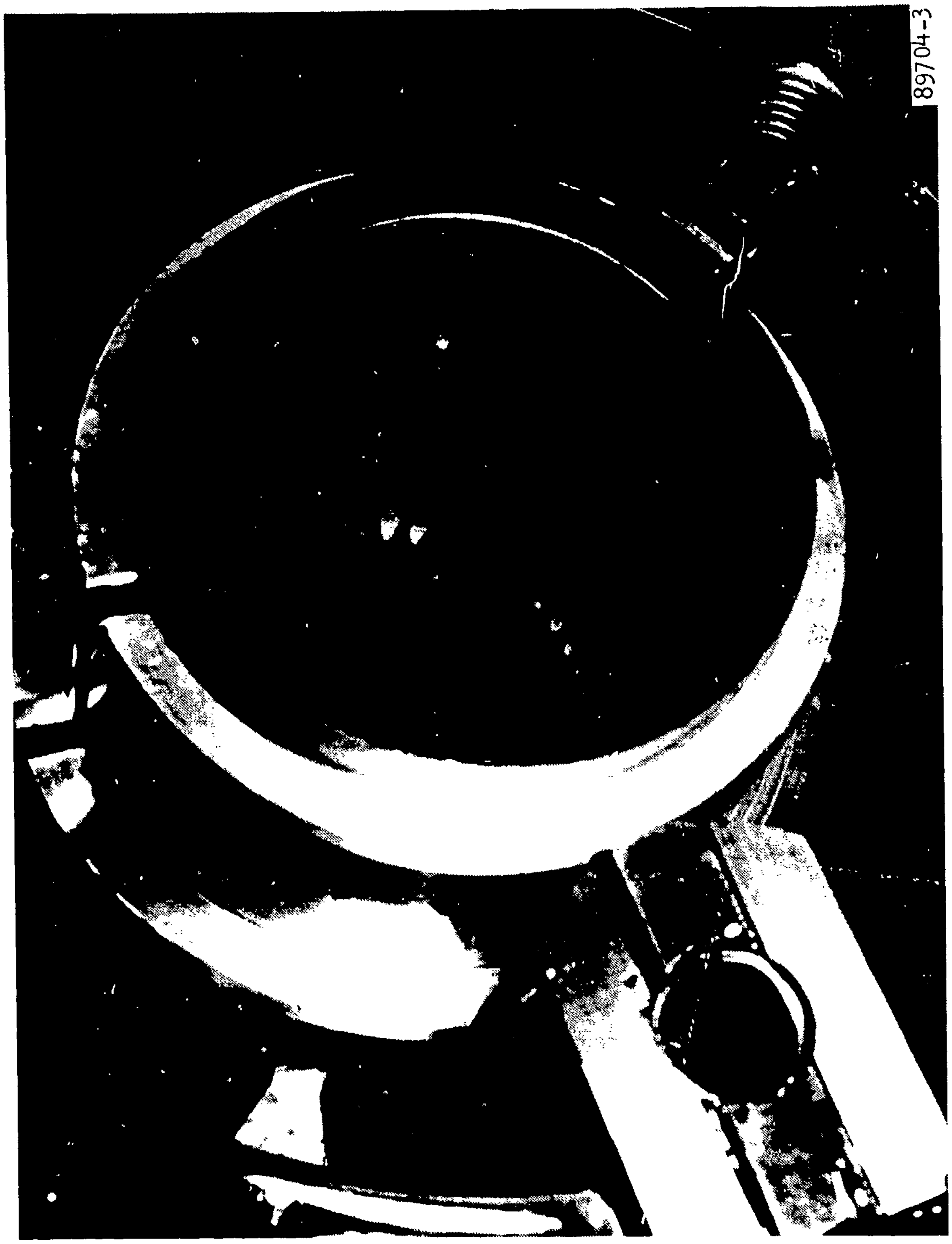


Figure 5-8. Completed Internal Spline

K-10473

TABLE 5-1

SLOT INSPECTION RESULTS
(Ref. Figure 2-4)

Slot No.	Degrees	Minutes	Seconds	Decimal* Degrees	Remarks
1	16	2	30	16.042	0.033-in. angular grind mark (see Figure 5-5)
2	15	58	54	15.982	
3	16	1	58	16.032	
4	16	2	22	16.039	
5	16	1	33	16.026	0.0038-in.-deep crescent grind mark (see Figure 5-6)
6	16	0	12	16.003	
7	15	57	24	15.957	
8	15	58	22	15.973	
9	16	0	0	16.000	Grind mark approx 1/2 in. dia by 0.0023 in. deep
10	16	1	16	16.021	
11	15	59	48	15.997	
12	15	59	38	15.994	
13	16	1	18	16.022	
14	16	2	5	16.035	

*Drawing requirement = 16.119 max.
15.894 min.

Figure 5-9. Rotor Slot Angle Position

K-10474

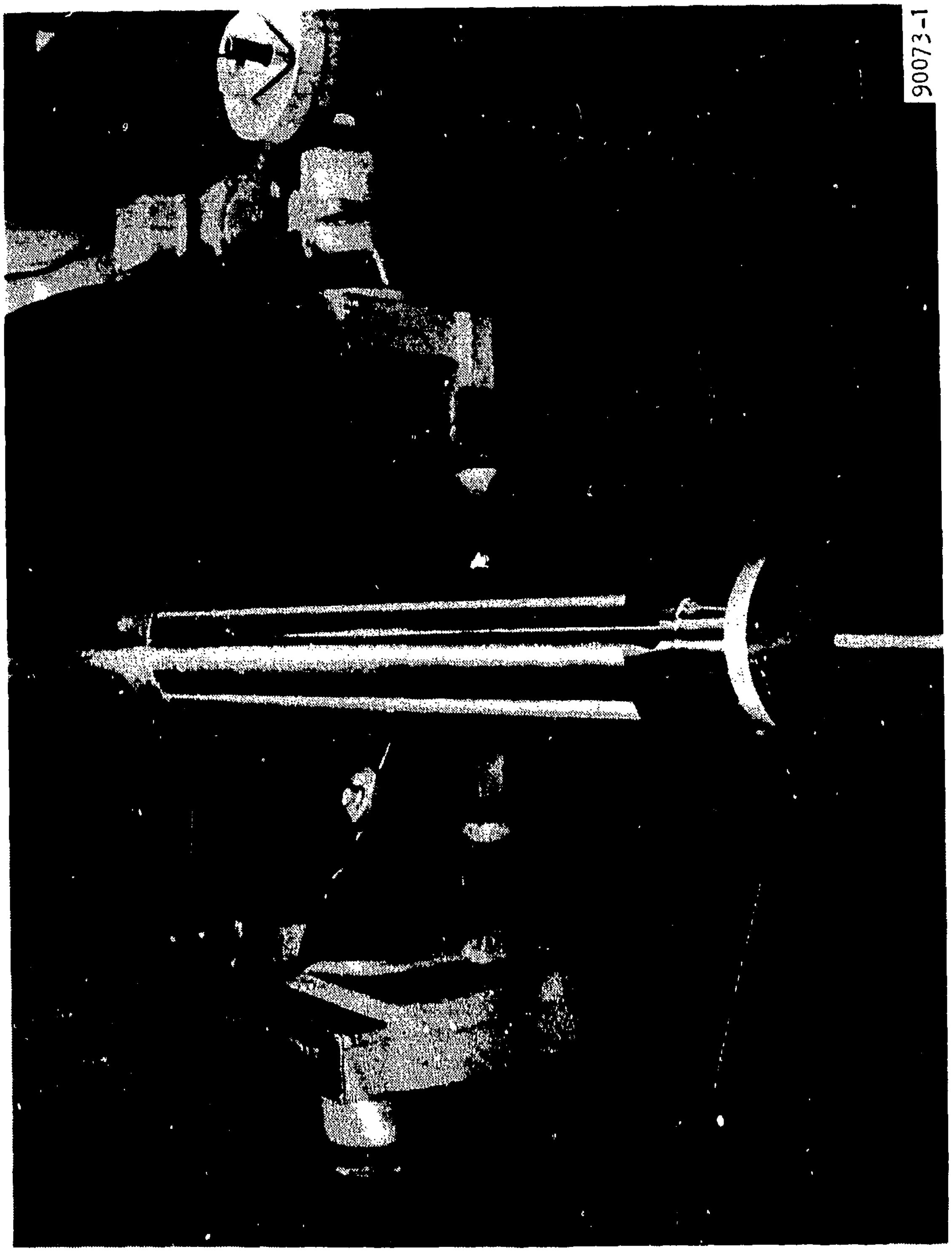


Figure 5-9 (Continued)

K-10475

6. MAGNET ASSEMBLY

Magnet assembly fixture 520560 (see Figures 6-1 and 6-2) was used to install shims and magnets in the rotor. The shims absorb any dimensional discrepancies between the magnets and the slots. Perforations were chem-milled through the shims to increase cushioning ability. Twenty-eight .008-in.-thick, pure nickel shims were spot welded to the slot sides using a Unitek model 1-132 spot welder (see Figure 6-3). A 40-watt-second reverse-polarity pulse was used. The welds were spaced approximately 3/16 in. apart around the periphery of the shim. Shim stock overlapped the insertion end of the rotor to allow sufficient stock for foldover (see Figure 6-4). This reduced the possibility of the magnet tearing the shim during insertion. The folded shim was cut flush with the slot edge before the end plates were installed.

Magnets were positioned to provide a relatively even magnetic force around the rotor. The magnets were previously measured in a Hemholtz coil by the vendor, and relative strength values were assigned. The location of each magnet and its relative strength is shown in Table 6-1.

Magnets tended to dive into the slot unless they were moved high in the slot. Steel keepers were installed to keep magnets in position during magnet installation and rotor handling. Teflon and polyethelyne tubing was placed under the magnets to prevent movement toward the slot bottom (see Figure 6-5). The tubing remained in place during magnet spinup.

Following magnet installation the shim stock was trimmed flush with the rotor end, end plates were heated to 350°F and installed on the rotor shaft. The rotor was drilled through a previously machined pilot hole in the Inconel end plate to provide for installation of a anti-rotation pin.

6.1 SLEEVE FABRICATION

The 1/8-in. Inconel 718 sleeve, PN 2007991, was rolled and welded at Valley Metal Works in El Cajon, California. AiResearch installed the sleeve in a 3/4-in. thick aluminum tube which doubled as a machining fixture and heat sink. The aluminum tube was heated to 350°F and a chilled Inconel sleeve inserted. The Inconel sleeve was 0.03-in. out of round and required plugs at each end to round it out. The sleeve was lowered into the hot aluminum tube with a rope and pulley. An air-escape hole was provided at the end of the tube to allow installation without air pressure buildup. The tube and sleeve combination was shipped to Margolian Honing Co. in Montebello, California for I.D. honing. Following honing, 10 thermocouples were installed (see Figure 6-6) to monitor temperature during sleeve and rotor installation. Thermocouples were installed by drilling 3/8-in. holes through the aluminum heat sink and spot welding the thermocouples directly to the sleeve. Welding the thermocouples to the sleeve, as opposed to touch contact, ensured accurate monitoring of sleeve temperature.

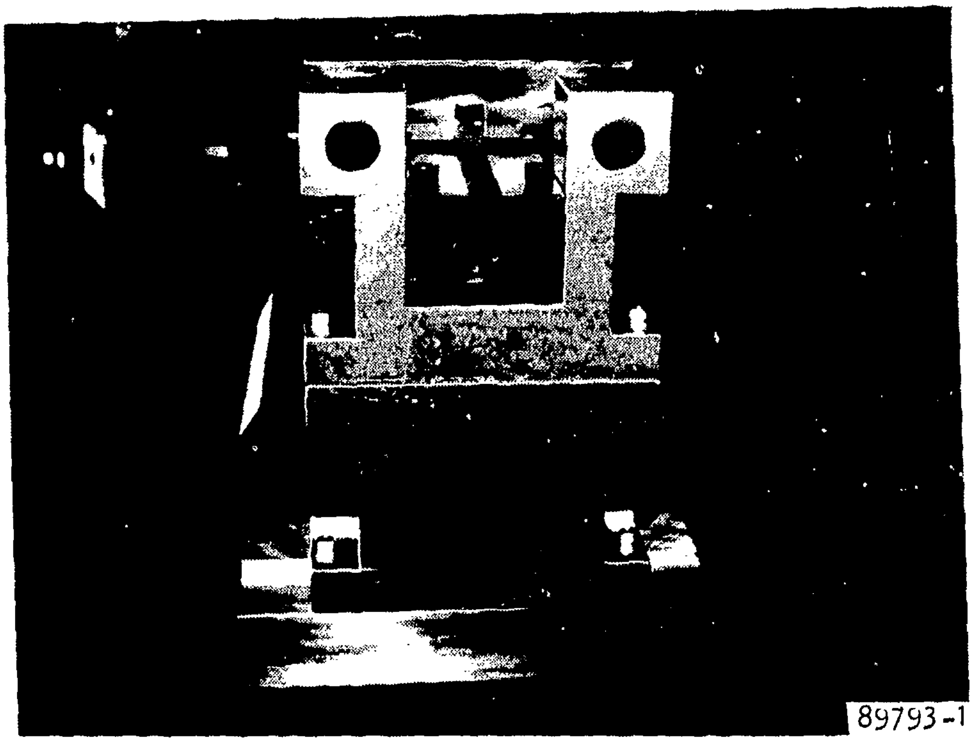


Figure 6-1. Magnet Assembly Fixture 520560

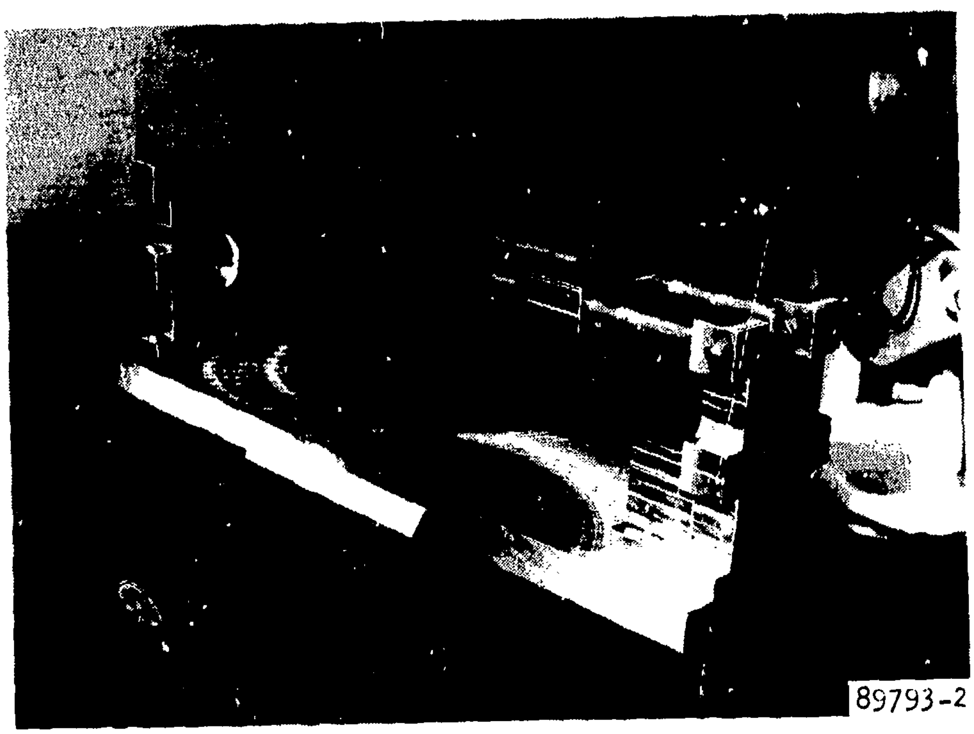


Figure 6-2. Magnet Assembly Fixture 520560

K-10476

Figure 6-3. Unitek Model 1-132 Spot Welder

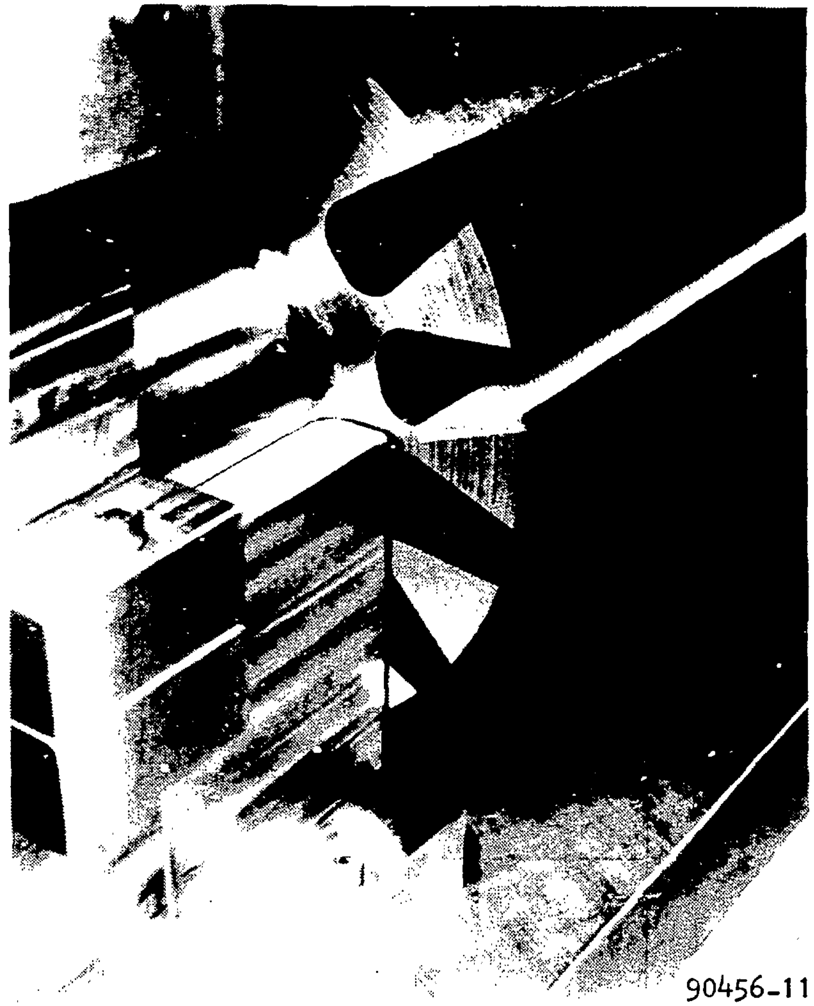


Figure 6-4. Shim Stock Overlap

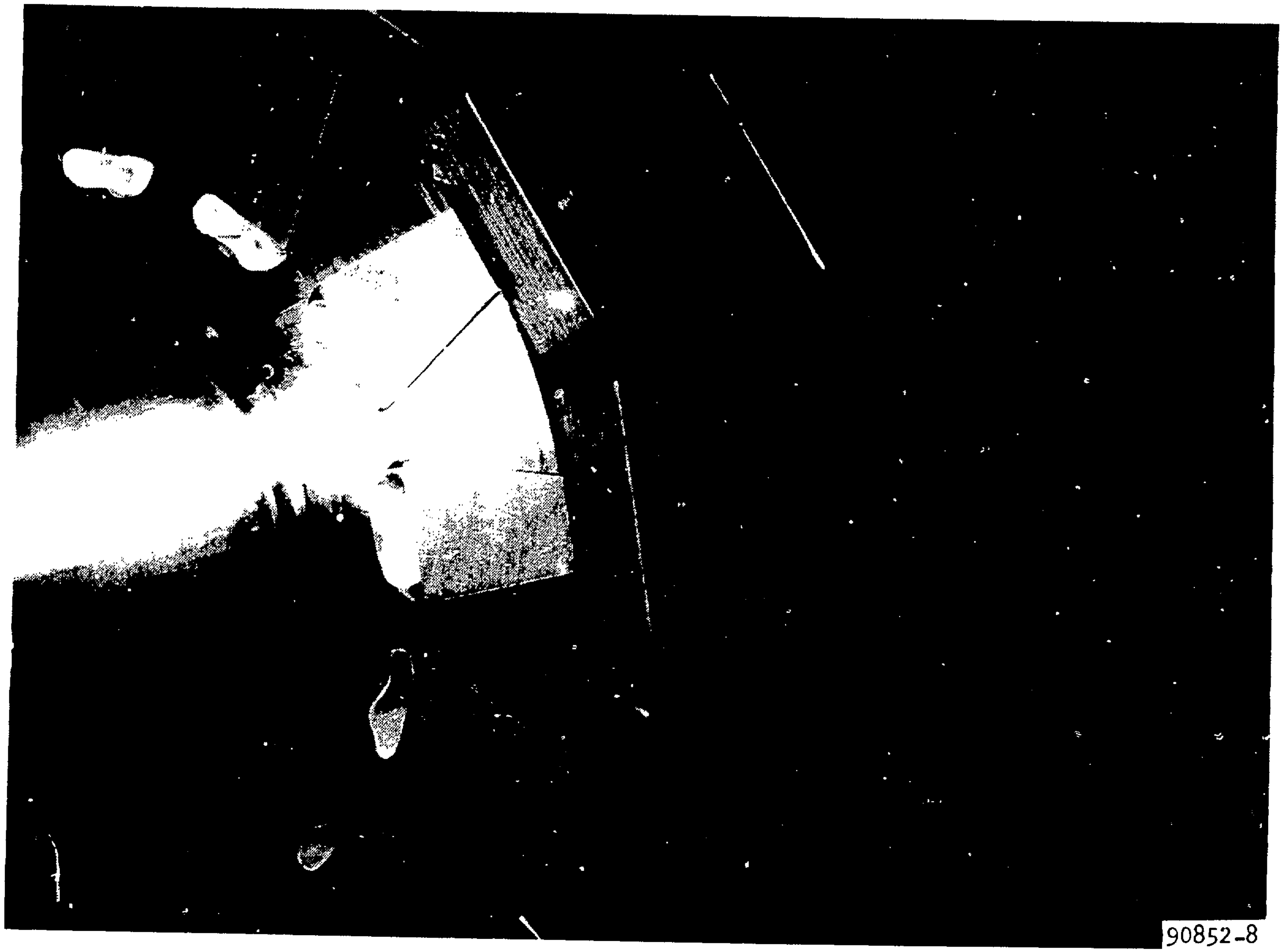
K-10477

TABLE 6-1

AS-BUILT MAGNET LOAD DATA SHEET

Slot No.	Rotor Axial Position										
	1	2	3	4	5	6	7	8	9	10	11
1	320	314	315	310	308	328	307	309	321	312	324
2	320	314	314	312	309	325	305	310	317	313	322
3	320	314	315	310	308	332	306	309	318	312	323
4	321	314	316	312	309	333	308	310	317	313	322
5	320	314	315	311	308	325	306	309	318	312	325
6	320	314	315	312	309	326	307	310	319	314	322
7	320	314	315	311	308	330	306	309	317	313	324
8	319	314	316	310	308	327	307	310	319	312	322
9	322	314	314	312	309	332	305	309	318	313	323
10	320	314	315	312	308	328	308	310	317	312	323
11	320	314	316	312	309	330	307	309	318	313	322
12	321	314	316	311	308	330	306	310	317	314	323
13	320	314	315	312	308	327	307	309	319	313	323
14	321	314	316	311	309	325	306	310	318	314	322

NOTE: Axial position 11 is at the spline end. Series 300 numbers represent the relative strength and location of each magnet.



K-10478

Figure 6-5. View Opposite Magnet Insertion End (NOTE: Tube stock will prevent downward magnet movement after keeps are removed.)

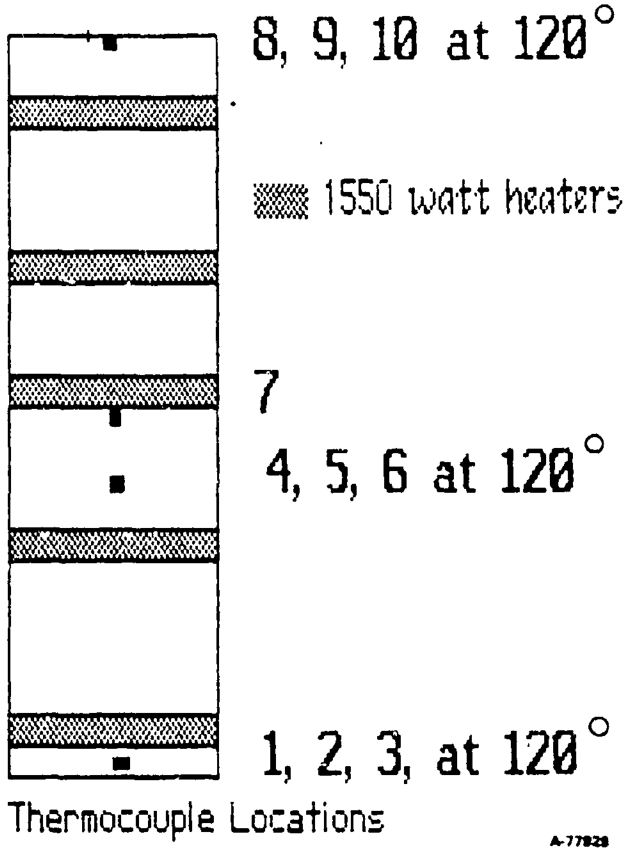


Figure 6-6. Thermocouple Locations on Heat Sink

6.2 FIRST SPIN

The rotor was initially spun with keepers (see Figures 6-7 and 6-8) in place to 680 rpm to check out the fixture. Hardware and instrumentation seemed to be acceptable, so the keepers were removed. The spinning was started, but maximum achievable speed was 180 rpm. A search coil was used to check the magnetic flux at the rotor end. The flux readings were high, and this was determined to be causing eddy currents within the aluminum end plates and frame. Nonstructural areas of the aluminum frame end plates were machined to increase the gap between the frame and rotor.

The rotor was spun to 9700 rpm with two balance weights at each end, 180 deg apart (i.e. not balanced). Imbalance due to magnet movement was not discernable. Maximum rotor displacement during this period was 0.005 in.

6.3 FIRST ROTOR MAGNET GRIND

Following the first spin, the rotor was wiped clean with MEK, air dried, and coated with Scotchweld structural epoxy to fill in low spots and magnet chips. This was cured at 240°F in the shipping box to provide a slow uniform heating for 9 hr.

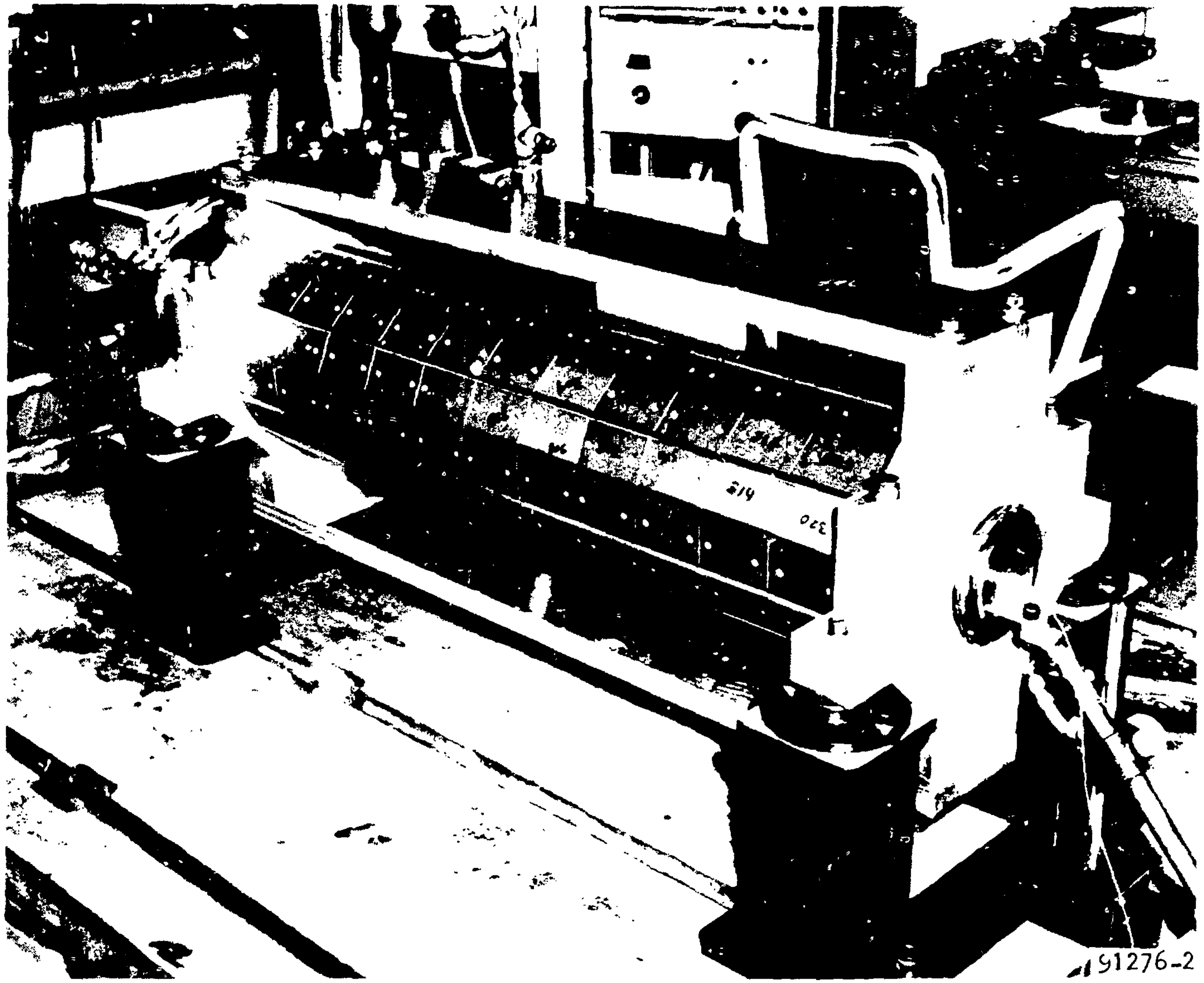


Figure 6-7. Rotor in Spin Fixture for Prespin Check

K-10479

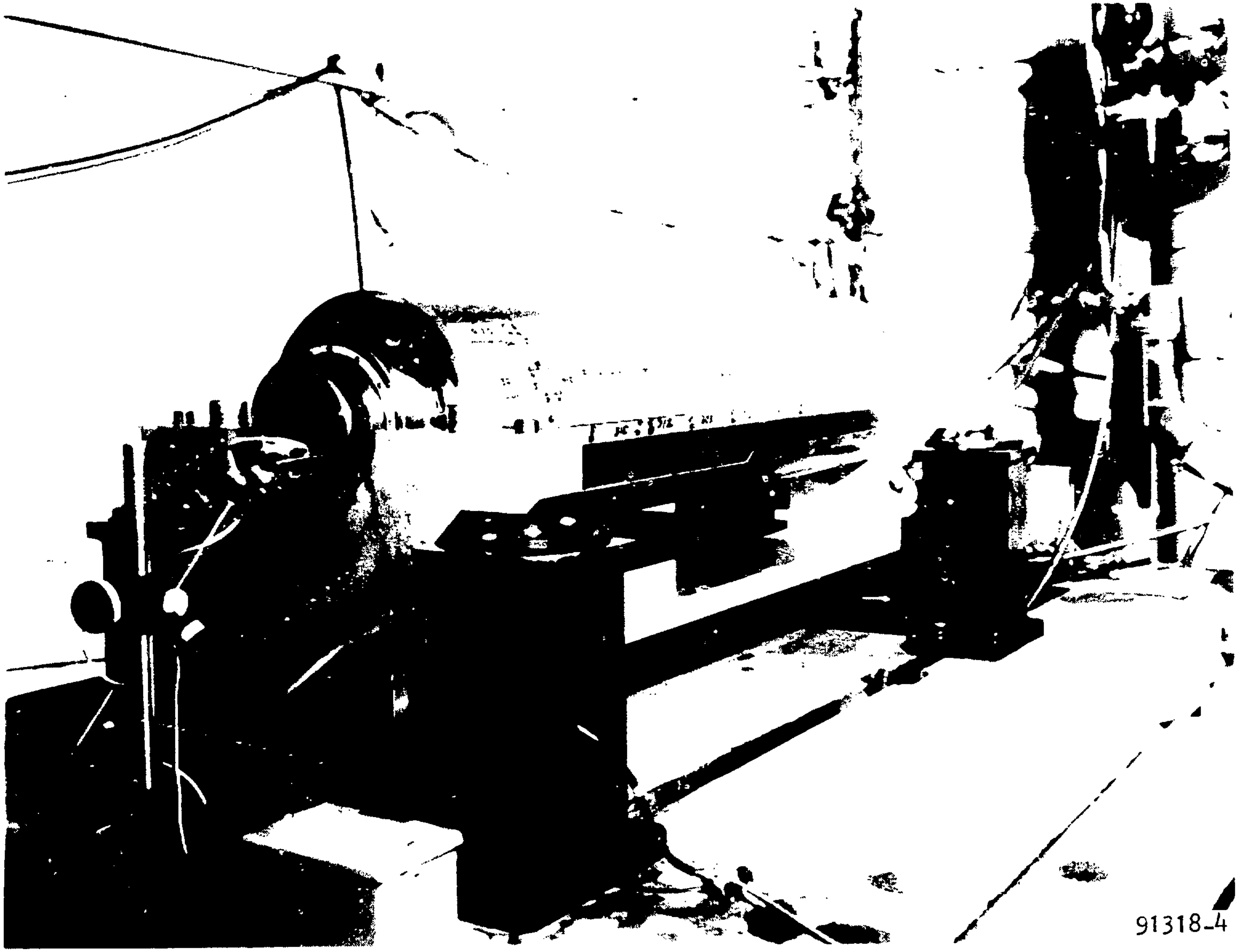


Figure 6-8. Rotor in Spin Fixture, Upper Half Removed

K-10480

Outside diameter grinding was performed at Quality Grinding in Huntington Park, California. Figure 6-9 shows the grind operation in process. Rotor dimensions were taken by placing the rotor on a surface plate and using a dial indicator to compare rotor diameter with standard gage blocks. The measured rotor outside diameter was 7.819 to 7.820 in.

6.4 FIRST SLEEVE INSTALLATION

Prior to installation of the sleeve and the rotor, a dummy rotor, simulating size and mass of the actual rotor, was installed in the press to check rotor insertion speed. A speed equivalent to an insertion time of 1.46 sec. was found to have the least rotor bounce as the rotor came to the end of its stroke. Speed was controlled by providing a back pressure on the air cylinder exhaust with full 100-psi pressure on the air cylinder inlet. The actual rotor was installed in the press and adjusted to stop within .075 in. of the sleeve support plate. Figure 6-10 shows the rotor installation setup. An air cushion stop within the air cylinder controls the stop. There was some concern that a hard metal-to-metal stop could damage the magnets.

The sleeve was heated to 600°F (see Table 6-2) and the rotor was inserted. The rotor remained in the sleeve and heat sink for 16 sec before the air cylinder was reversed to withdraw the rotor and sleeve from the heat sink. Initially the heat sink stuck to the rotor and rose with the sleeve. A hammer tap on the heat sink freed it from the rotor sleeve. The rotor and sleeve were elevated for cooling. Total contact time, rotor to heat sink, was 56 sec. A CO_2 fire extinguisher had been kept nearby in case the heat sink stuck to the sleeve and required immediate cooling. Figures 6-11 and 6-12 show the sleeve installation.

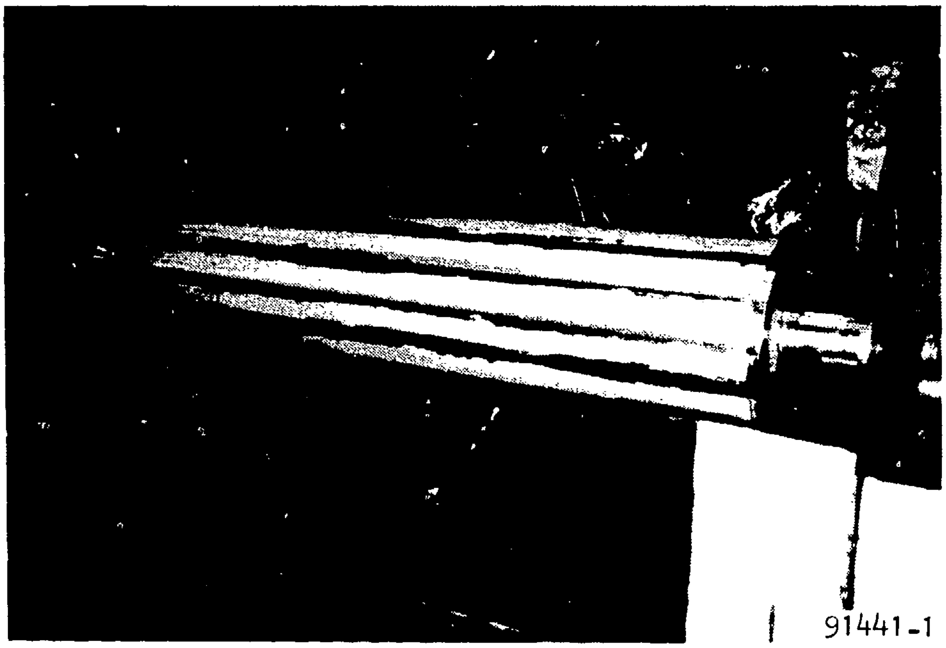
Lt. Neal Harold, Air Force project engineer, witnessed the sleeve installation.

The installed sleeve was ground to its finished diameter at Quality Grind in Huntington Park. The sleeve was dye-penetrant-checked for cracks after grind, and none were found.

6.5 FIRST SLEEVE SPIN TEST

The objective of this operation was to spin the rotor to maximum design speed plus 10 percent or 19,800 rpm. The magnets were expected to lock in at their maximum outer position. The 0.032-in.-thick Inconel sleeve was designed to accommodate this distortion.

Actual speed achieved was 19,100 rpm, which fell short of the design requirement of 19,800 rpm. The test was terminated due to a rotor displacement of 0.005. Examination of the rotor revealed several bumps in the surface that were later determined to be broken magnets. See Figure 6-13. Table 6-3 displays the measurement of rotor leeve deformation after speeds of 15,000 and 19,000 rpm.



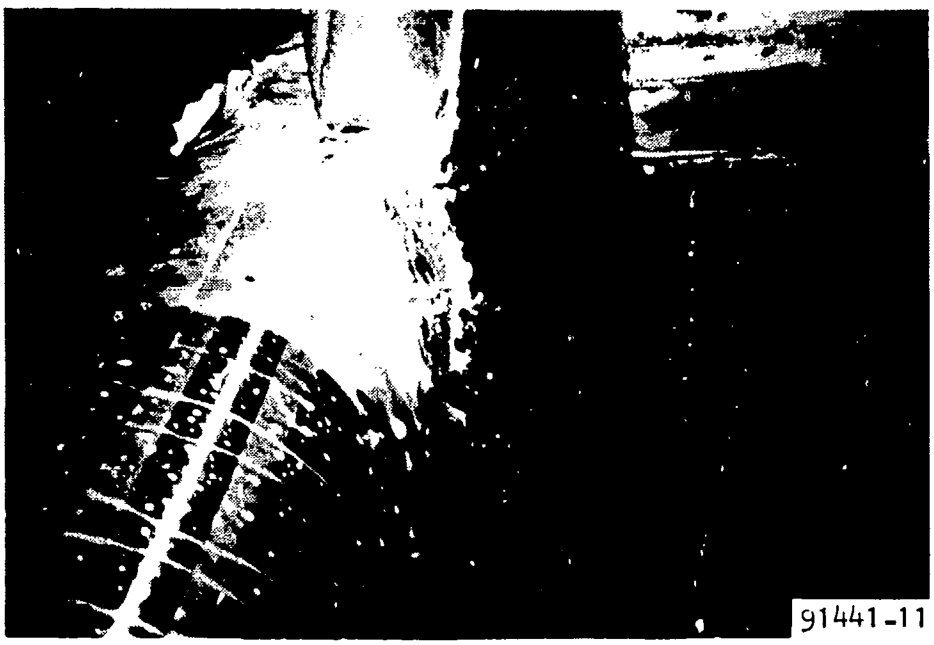
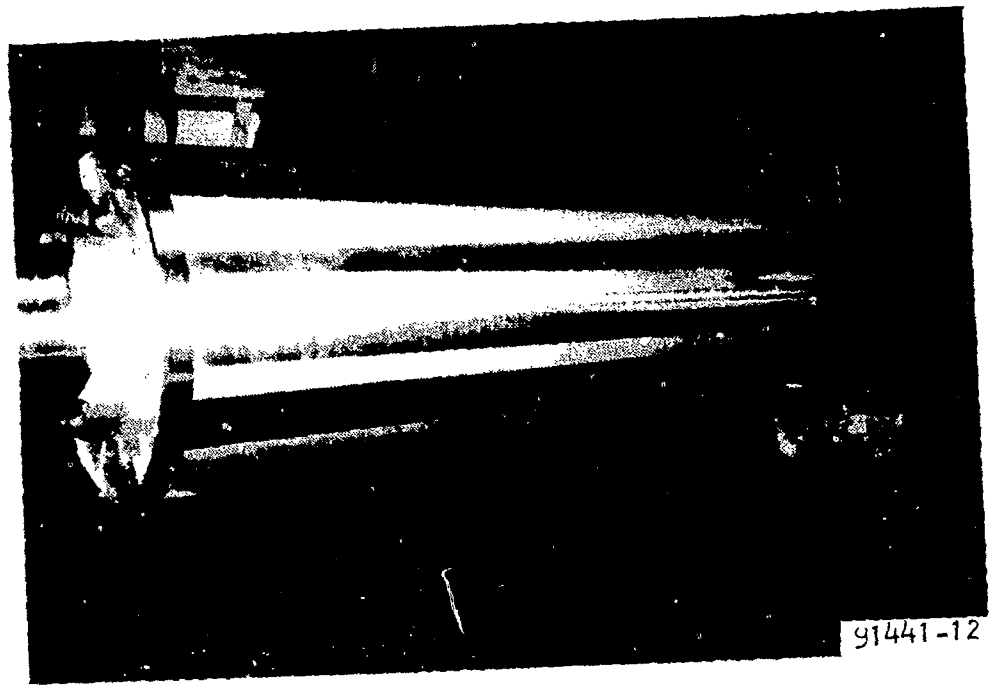


Figure 6-9. Grind Operation in Process

K-10481



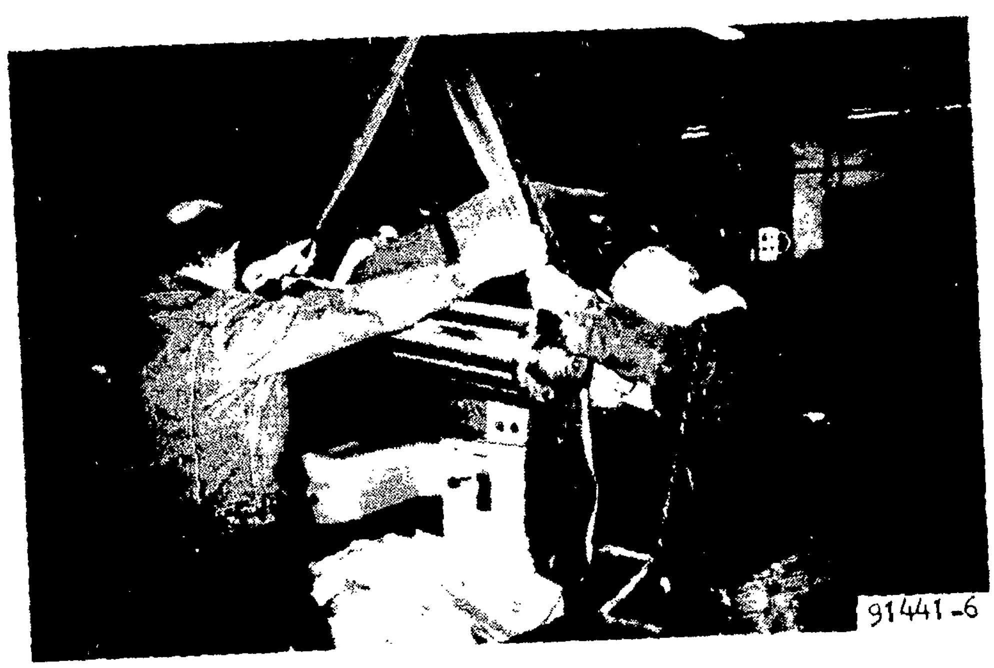


Figure 6-9 (Continued)

K-10482

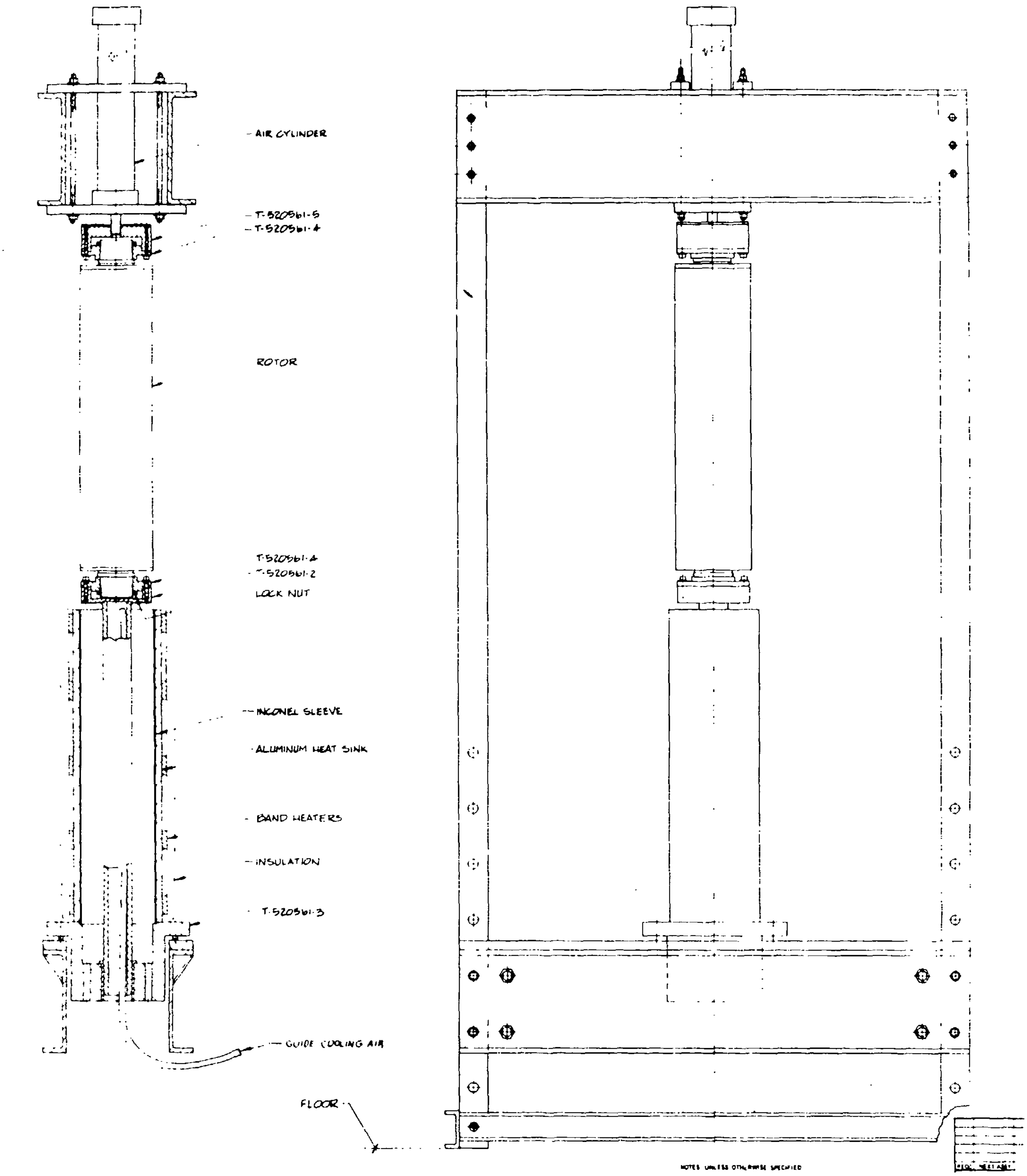


Figure 6-10. Rotor Installation Setup

A-78149

TABLE 6-2

SLEEVE TEMPERATURE PRIOR TO ASSEMBLY

File: MW SLEEVE TEMP
Report: THERMOCOUPLE TEMP °F

Time	TC-8	TC-4	TC-7	TC-1	TC-10
7:35 a.m.	90	80	86	72	72
7:45 a.m.	250	207	224	117	122
7:55 a.m.	387	353	369	216	253
8:05 a.m.	378	422	409	316	323
8:15 a.m.	375	487	462	490	414
8:25 a.m.	387	518	491	503	387
8:35 a.m.	401	543	516	565	403
8:40 a.m.	429	563	540	581	430
8:45 a.m.	464	586	567	597	474
8:50 a.m.	536	612	599	615	557
8:55 a.m.	627	612	610	608	672

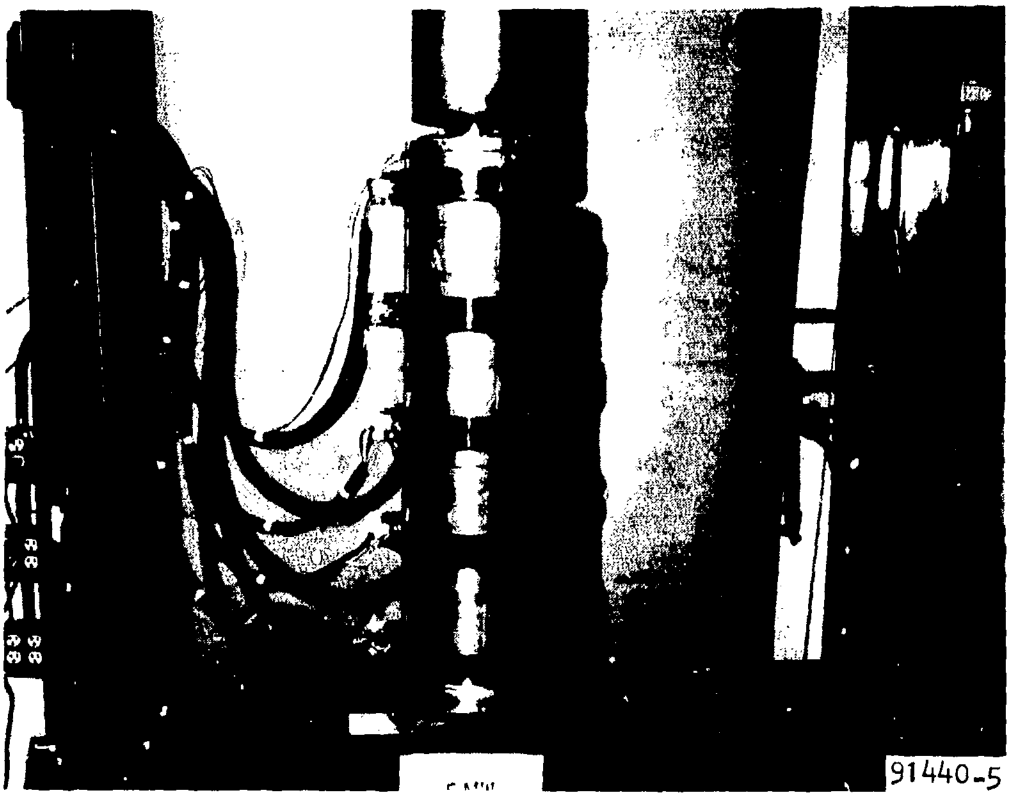


Figure 6-11. 1550-Watt Band Clamp Heaters Installed on Heat Sink

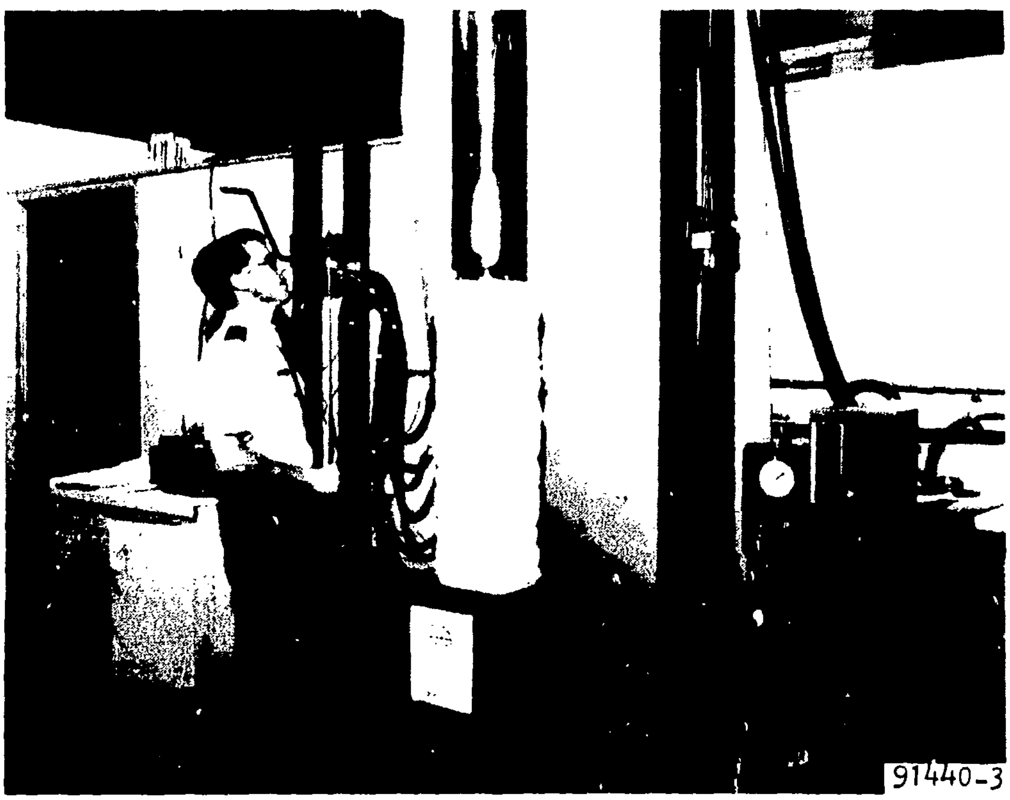
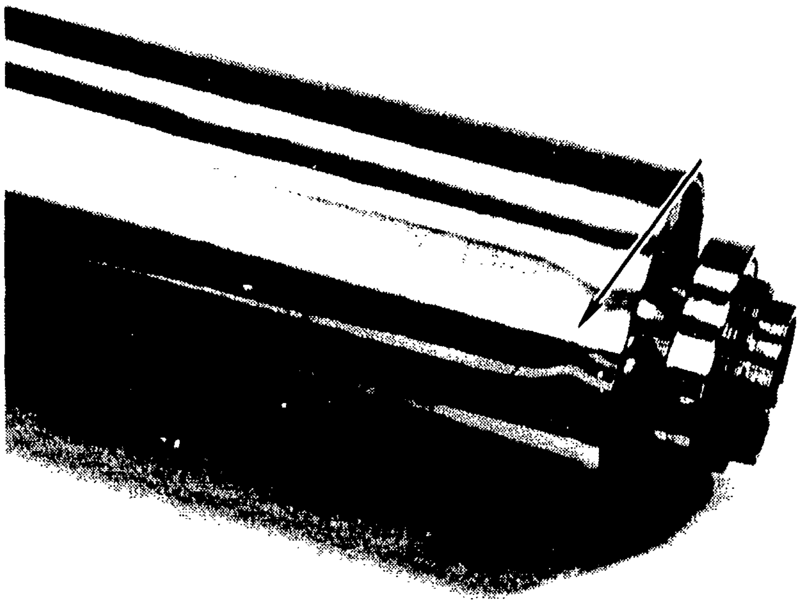
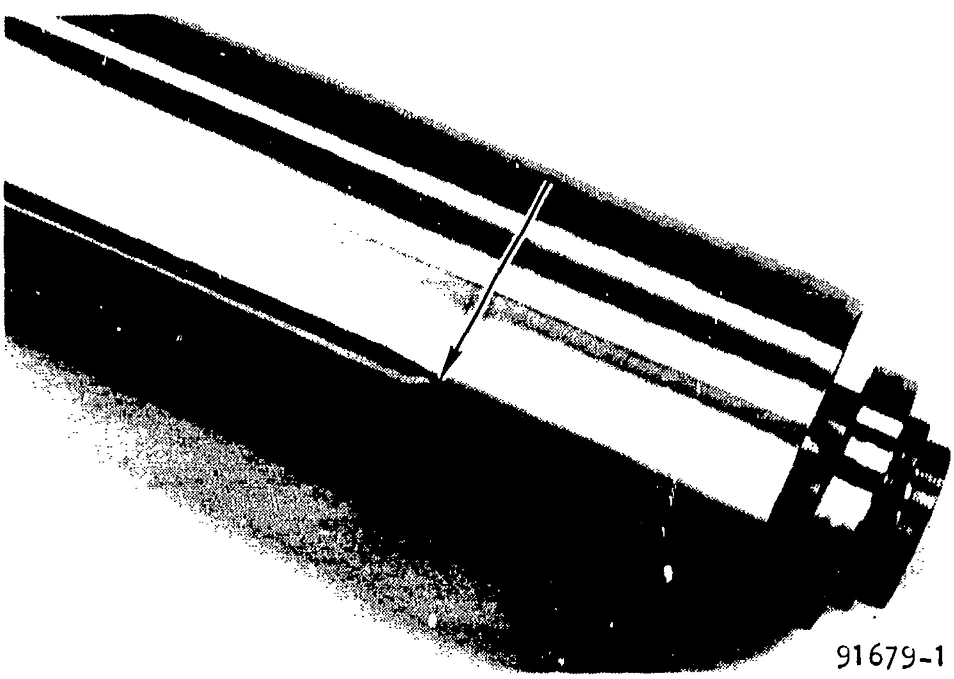


Figure 6-12. Lt. Harold Observing Sleeve Installation
(Note ceramic wool insulation around heat sink)

F-47025



91679-2



91679-1

Figure 6-13. Two Views of Bumps Attributed to Magnet Separation

K-10483

TABLE 6-3

ROTOR SLEEVE DEFORMATION AFTER 15,000 AND 19,100 RPM

Location	4 in.		12 in.		20 in.		28 in.		Total After	Total After
RPM	15,000	19,100	15,000	19,100	15,000	19,100	15,000	19,100	15,000	19,100
Slot 1	0	0	0	0	0	0	0	0	0	0
	18	20	14	24	8	22	3	20	43	86
Slot 2	3	0	0	2	0	4	0	4	3	10
	17	21	12	19	6	22	10	28	45	90
Slot 3	3	0	0	0	-1	5	0	3	2	8
	12	16	10	10	14	24	13	27	49	77
Slot 4	4	-1	-2	-3	0	7	1	3	3	6
	18	18	22	30	16	36	13	32	69	116
Slot 5	5	4	-3	-3	-1	4	1	5	2	10
	20	20	8	9	6	19	10	25	44	73
Slot 6	5	5	-4	-6	0	5	2	5	3	9
	19	20	21	23	11	21	6	17	57	81
Slot 7	4	6	-1	-2	0	5	-2	2	1	11
	10	27	12	8	5	16	10	28	37	79
Slot 8	0	7	-3	-2	-2	5	-2	8	-7	18
	12	22	19	22	3	19	14	33	48	96
Slot 9	0	11	-5	0	-5	8	3	8	-7	27
	17	33	12	24	18	37	10	25	57	119
Slot 10	5	12	0	8	1	9	2	5	8	34
	12	25	12	28	17	21	10	26	51	100
Slot 11	0	11	1	12	1	6	1	9	3	38
	13	44	8	45	4	36	18	38	43	163
Slot 12	4	6	3	12	0	9	-4	5	3	32
	22	21	6	17	8	12	4	12	40	62
Slot 13	7	7	0	8	-2	0	-4	-1	1	14
	21	23	11	14	4	13	4	20	40	70
Slot 14	4	6	-1	2	0	4	-3	0	0	12
	12	15	12	25	8	17	10	29	42	86
Total	267	399	164	326	119	386	130	416	680	1527
Total Highs	223	325	179	298	128	315	135	360	665	1298
Total Lows	44	74	-15	28	-9	71	-5	56	15	229
Hi-Low	179	251	194	270	137	244	140	304	650	1069
Average Mov/Slot	13	18	14	19	10	17	10	22	12	19

NOTES: All measurements are in mils.
Measuring starts at the non-drive end.
rotation is clockwise looking at drive end.
Dial indicator was reset to zero at each starting location.

A small section of the sleeve was removed by grinding to determine the cause of one bump. A broken magnet was verified to be the cause. The sleeve was not designed to carry loading of the magnets. The sleeve was expected to deform, but appeared to be soft. Sections of the sleeve were removed and machined into tensile test specimens. Test results verified that the material was solution-annealed but not age-hardened. The sleeve-fabricatiing vendor had stated that the sleeve fabrication did not include age-hardening, but this fact did not reach the AiResearch engineering department. The second sleeve was age-hardened as a result of this discovery. Results of the tensile test for age-hardened and solution-annealed samples are shown in Table 6-4.

6.6 SECOND ROTOR MAGNET GRIND

Prior to grind, the broken magnets pieces were removed and the depressions filled with Devcon F epoxy putty. Devcon F cures at room temperature.

The rotor was shipped to Quality Grinding for OD grind. During grinding some of the Devcon filler putty separated from the rotor. The affected areas were cleaned with acetone and new Devcon F putty applied. After room temperature cure, grinding was continued, and the epoxy adhered well. The rotor diameter was checked on the grind machine by using a "pi" tape. A final dimensional check was made on a surface plate with "jo blocks" and a dial indicator. The finished rotor outside diameter ranged from 7.8123 to 7.8125 in. per Figure 2-1 on page 2-3 of this document. See Figure 6-14.

6.7 SECOND SLEEVE INSTALLATION

The sleeve (see Figure 6-15) was thermocoupled in the same manner as the first sleeve. The installation press air cylinder was adjusted to install the rotor in the sleeve in approximately 1.5 sec. See Figure 6-16. The rotor was heated with band clamps, and temperatures were recorded as shown in Table 6-6. Actual rotor insertion time was 0.8 sec; this was twice as fast as the desired time of 1.5 sec. Air cylinder adjustment may have changed due to variations in shop air pressure. The aluminum heat sink stuck to the rotor as the air cylinder lifted the rotor. Lead hammers were used in the attempt to break the heat sink loose. The rotor was raised against the air cylinder top stop (not at full acceleration) to provide a small impact shock on the rotor/heat sink joint; this action separated the heat sink from the rotor. Total contact time, rotor-to-heat-sink, was approximately 2 min. Thermal analysis revealed that the mass of aluminum did not have sufficient latent heat with the strap heaters turned off, to damage the magnets. Future sleeve installations of this type should use a wood frame to apply pressure to the heat sink as the air cylinder raises the rotor.

6.8 SECOND SLEEVE GRIND

The rotor was transported to Quality Grinding Inc., for OD sleeve grinding. The finished-rotor-and-sleeve diameter was measured by placing the rotor on a surface plate, establishing a fixed dimension with precision gage blocks and comparison measuring with a long-stem dial indicator. The long stem was required to minimize the effects of magnetism on the indicator. Rotor-and-sleeve outside diameter measured 7.8830 to 7.8825 in. This provided for a

TABLE 6-4

INCONEL 718 SLEEVE TENSILE TEST RESULTS

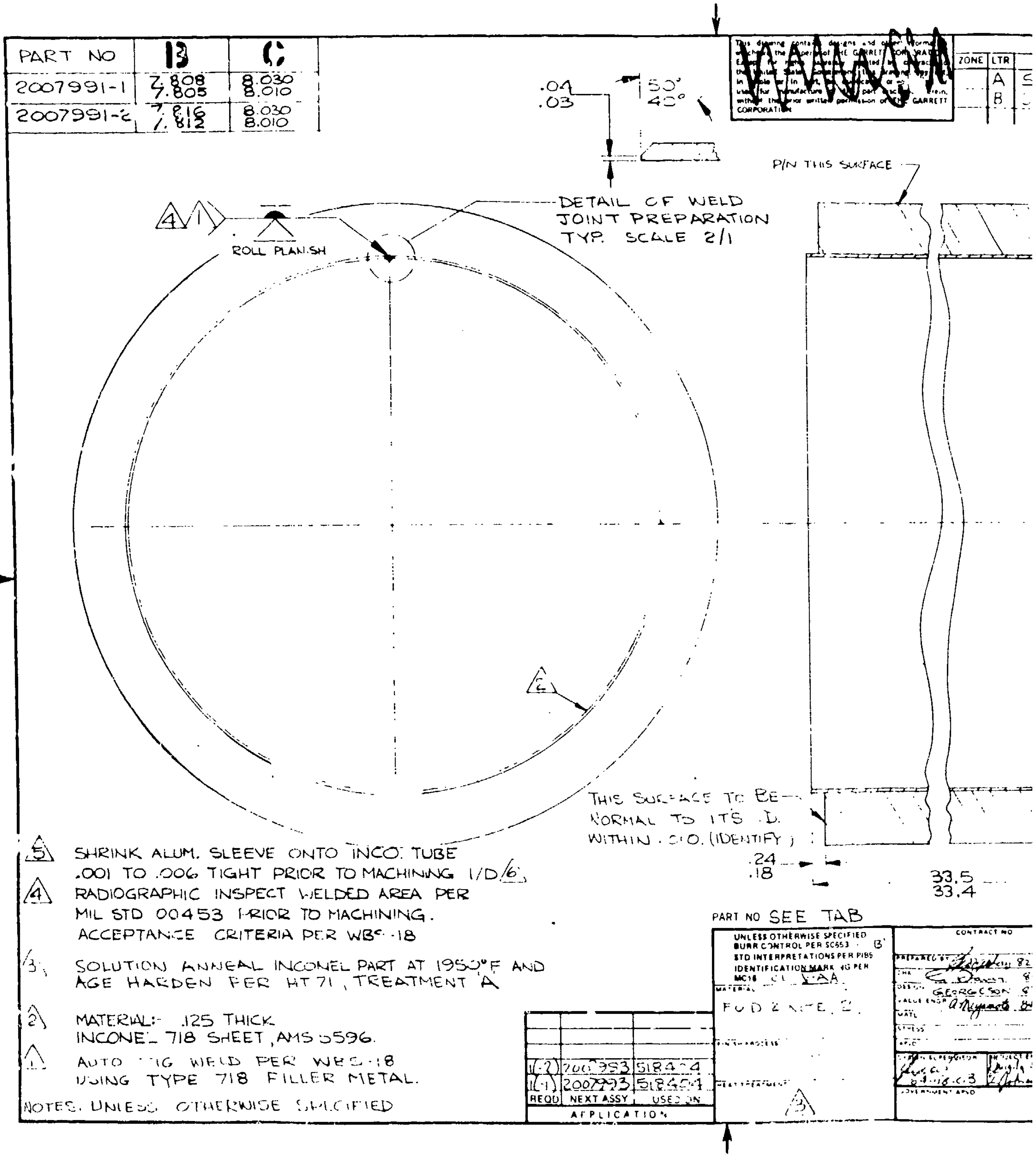
Specimen No.	Ultimate ksi	Yield ksi	% Elong.	Note
1	198.3	156.5	22	1,3
2	196.5	156.3	22.5	1,3
3	197.3	152.7	23	1,3
4	195.5	151.2	18	1,4
5	193.2	148.9	18	1,4
6	192.9	147.4	18	1,4
7	119.5	58.0	59	2,3
8	120.4	55.7	55.5	2,3
9	120.1	58.0	55.5	2,3
10	117.2	58.0	48	2,4
11	115.5	60.6	50.5	2,4
12	116.5	58.5	50	2,4
Sol. Annealed	140 max.	80 max.	30 min.	5
Age Hardened	180 min.	150 min.	12 min.	6

Notes:

1. Tensile properties in the age-hardened condition.
2. Tensile properties in the solution-annealed condition.
3. Specimen oriented in the axial direction with respect to the part.
4. Specimen oriented in the hoop direction with respect to the part.
5. Maximum and minimum requirements per AMS 5596 for solution-treated condition.
6. Minimum requirements per AMS 5596 for age-hardened condition.

Figure 6-14. Rotor

K-10484


PART NO
B
C
2007991-1
7.808
7.805
8.030
8.010
2007991-2
7.816
7.812
8.030
8.010
.04
.03
50°
40°
DETAIL OF WELD
JOINT PREPARATION
TYP. SCALE 2/1
P/N THIS SURFACE
ROLL PLANISH
THIS SURFACE TO BE
NORMAL TO ITS .D.
WITHIN .010. (IDENTIFY)
.24
.18
33.5
33.4
5 SHRINK ALUM. SLEEVE ONTO INCO. TUBE
.001 TO .006 TIGHT PRIOR TO MACHINING I/D 6
4 RADIOGRAPHIC INSPECT WELDED AREA PER
MIL STD 00453 PRIOR TO MACHINING.
ACCEPTANCE CRITERIA PER WBS-18
3 SOLUTION ANNEAL INCONEL PART AT 1950°F AND
AGE HARDEN PER HT 71, TREATMENT A
2 MATERIAL:- .125 THICK
INCONEL 718 SHEET, AMS 5596.
1 AUTO TIG WELD PER WBS-18
USING TYPE 718 FILLER METAL.
NOTES: UNLESS OTHERWISE SPECIFIED
(-2) 2007993 518454
(-1) 2007993 518454
REQD NEXT ASSY USED ON
APPLICATION
PART NO SEE TAB
UNLESS OTHERWISE SPECIFIED
BURR CONTROL PER SC653
STD INTERPRETATIONS PER PIBS
IDENTIFICATION MARK 4G PER
MC18
MATERIAL
FINISH PROCESS
HEAT TREATMENT
CONTRACT NO
PREPARED BY
GEORGESON
GOVERNMENT APVD
ZONE LTR
A
B

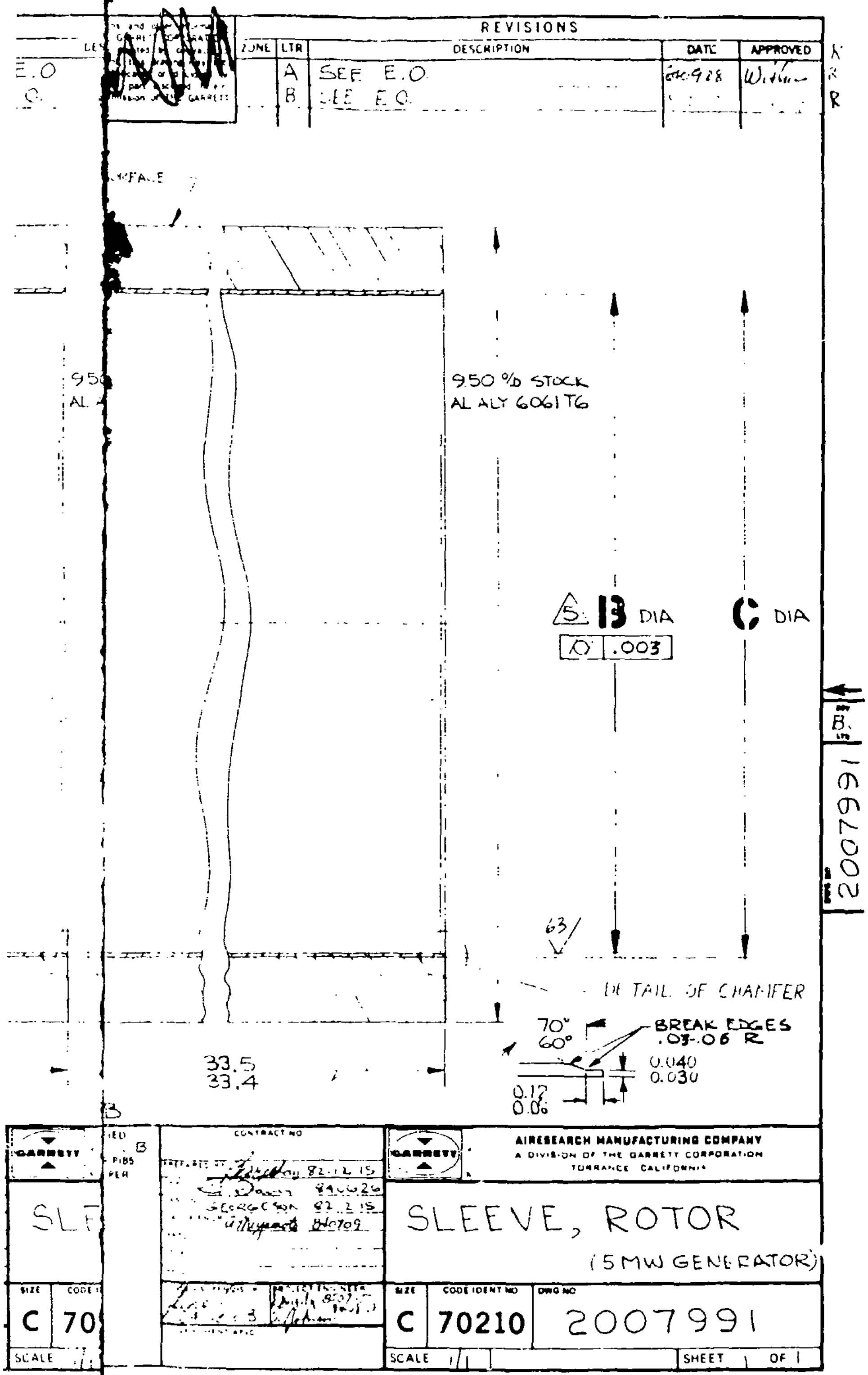


Figure 6-15. Sleeve. Rotor
(5 mw Generator)

2

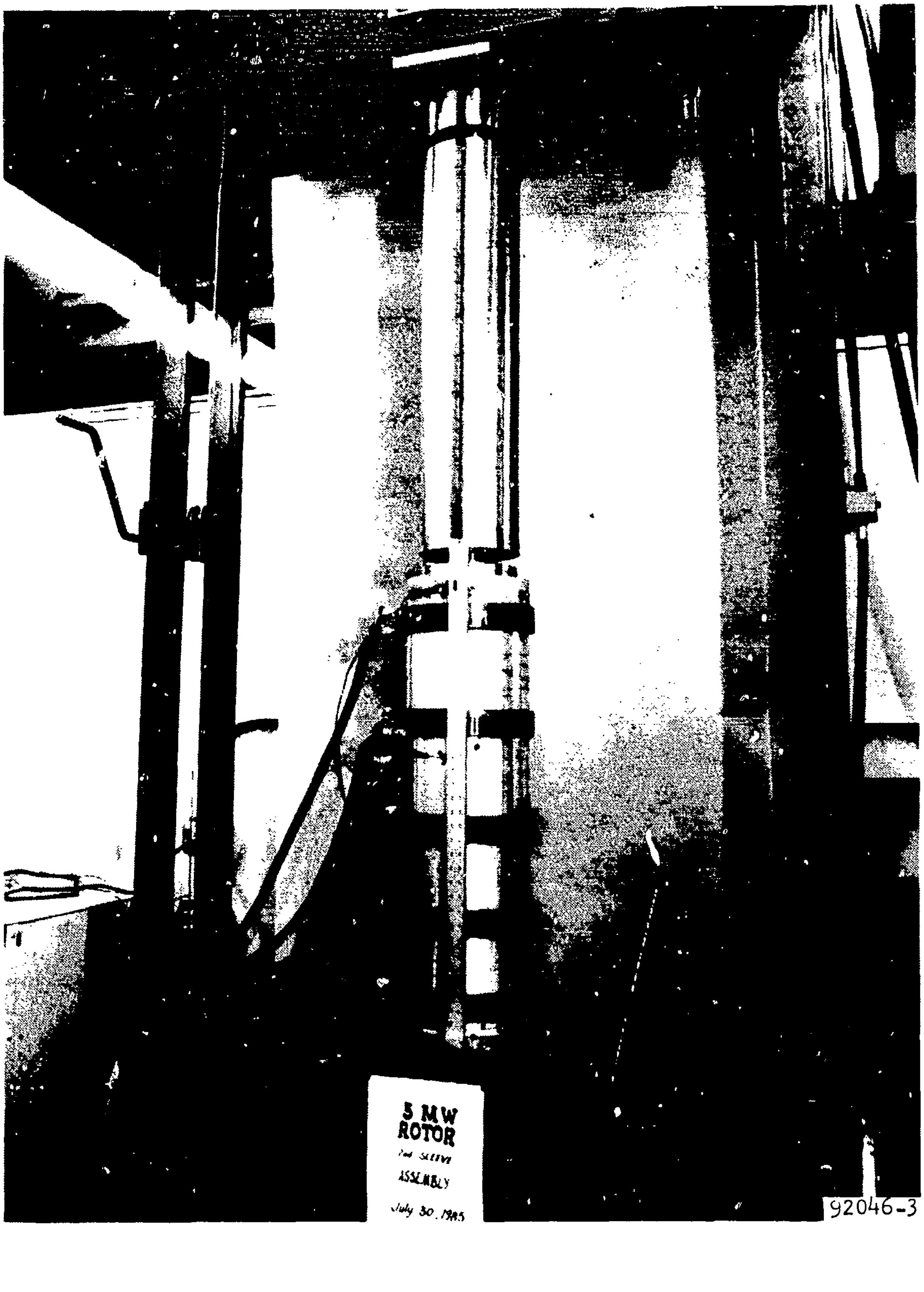


Figure 6-16. Rotor and Heat Sink Prior to Installing Insulation

K-10485

TABLE 6-5. SLEEVE HEATING SCHEDULE

Actual Time, a.m.	Sleeve Temperature, °F									
	Thermocouples at Top			Thermocouples at Center				Thermocouples at Bottom		
	1	2	3	4	5	6	7	8	9	10
9:02	179	152	188	157	187	185	151	197	199	165
9:06	268	253	291	257	291	276	257	285	274	236
9:11	326	318	359	312	353	320	309	308	313	265
9:13	355	348	388	342	377	341	338	321	331	280
9:19	380	380	386	417	433	408	433	417	377	365
9:28	424	430	453	473	488	463	500	480	453	425
9:32	499	505	535	520	537	510	545	537	487	516
9:39	588	592	627	582	597	578	604	569	525	576
9:42	621	629	643	634	640	634	650	600	570	551

10 percent increase in sleeve thickness over sleeve 1. The increase in thickness was designed to provide for the retention of small pieces of broken magnets. A sleeve designed to contain the entire magnet weight (117 lb) would severely reduce generator performance.

6.9 SECOND SLEEVE SPIN TEST

The second sleeve was initially spun up in the low-energy missile test cell at the AiResearch Los Angeles facility. The unit was run to 13,000 rpm and shut down due to excessive rotor displacement. The rotor developed bumps on the surface similar to those observed during the first spin operation. The bump height was measured with a teflon-tipped dial indicator. The teflon tip (4 in.) was used to reduce the effect of the rotor magnetic field on the dial indicator. Measurements after runs at various speeds are shown in Table 6-6.* All measurements are related to the lowest adjacent rotor surface areas within the same axial position. The major bumps were predominantly in the areas of slots 12 and 13; however, all slots exhibited some growth (0.005 to 0.010 in.)

Because of bump growth and possible rotor instability, a decision was made to move the rotor to a high-energy test cell. A TV camera, monitor, and recorder were used to observe the rotor during test. During one run, the hydraulic line adapter ruptured with the resultant loss of hydraulic fluid in the test cell (Figure 6-17). Cleanup required several hours.

On August 21, 1985 the drive end bearing failed (Figure 6-18). The rotor coasted to a stop from 19,000 rpm. Although a shower of sparks emanated from the bearing, damage was limited to the bearing, aluminum seal plate, and thermocouple. The rotor was not damaged. Failure was attributed to excessive bearing loads due to rotor imbalance.

*Bump height varied during each run and at times decreased.

TABLE 6-6

BUMP HEIGHTS AT VARYING SPEEDS

Bump Height, in.							
Bump No.	At 15.5 rpm	At 16.0 rpm	At 16.5 rpm	At 17.0 rpm	At 17.3 rpm	At 18.0 rpm	At 18.5 rpm
1	0.040	0.045	0.010	0.015	0.015	0.012	0.015
2	0.042	0.042	0.010	0.015	0.010	0.012	0.015
3	0.022	0.026	0.003	0.006	0.000	0.000	0.002
4	0.027	0.042	0.006	0.012	0.008	0.005	0.007
5	0.008	0.014	0.009	0.010	0.008	0.009	0.012
6	0.018	0.039	0.020	0.026	0.025	0.027	0.031
7	0.017	0.022	0.010	0.024	0.022	0.022	0.024
8	0.022	0.029	0.030	0.032	0.032	0.037	0.034

NOTES:

1. Speed given in rpm (X 1000).
2. Drive end is close to Bump 1.

Repairs were made and the rotor was spun to 15,000 rpm when the hydraulic line broke for the second time. The hydraulic line was repaired, and the test continued. Accelerometers indicated G loading to be severe (14 to 26 G), as the rotor reached 12,800 rpm. The test engineer was not able to balance the rotor well enough to reduce the G loads.

AiResearch engineering, with Air Force concurrence, decided that, without knowing the condition of magnets under the sleeve, the risk of further overspeed outweighed possible benefits of continuing the test.

The sleeve was removed by grinding a cut line with a hand held "radiac" cutter over the pole piece adjacent to the magnet edge. Grind cuts were made along the length in two places 180 deg apart to allow splitting of the sleeve for removal with the least movement of the broken magnets. Figure 6-19 shows the magnet condition immediately following sleeve removal.

Broken magnet particles were removed to assess the damage. The deepest magnet "hole" was 1 in. Figure 6-20 shows exposed gaps due to broken magnets.

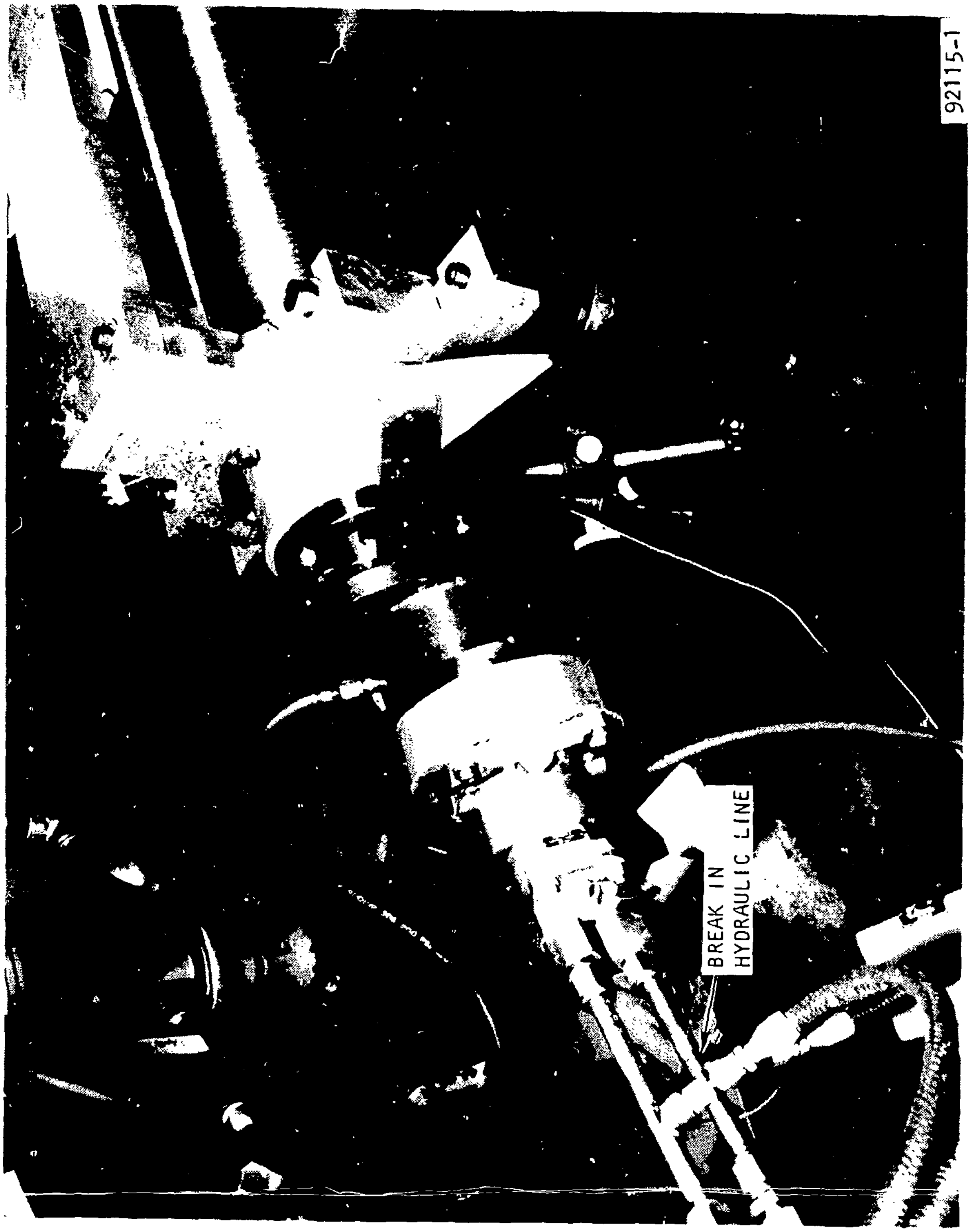
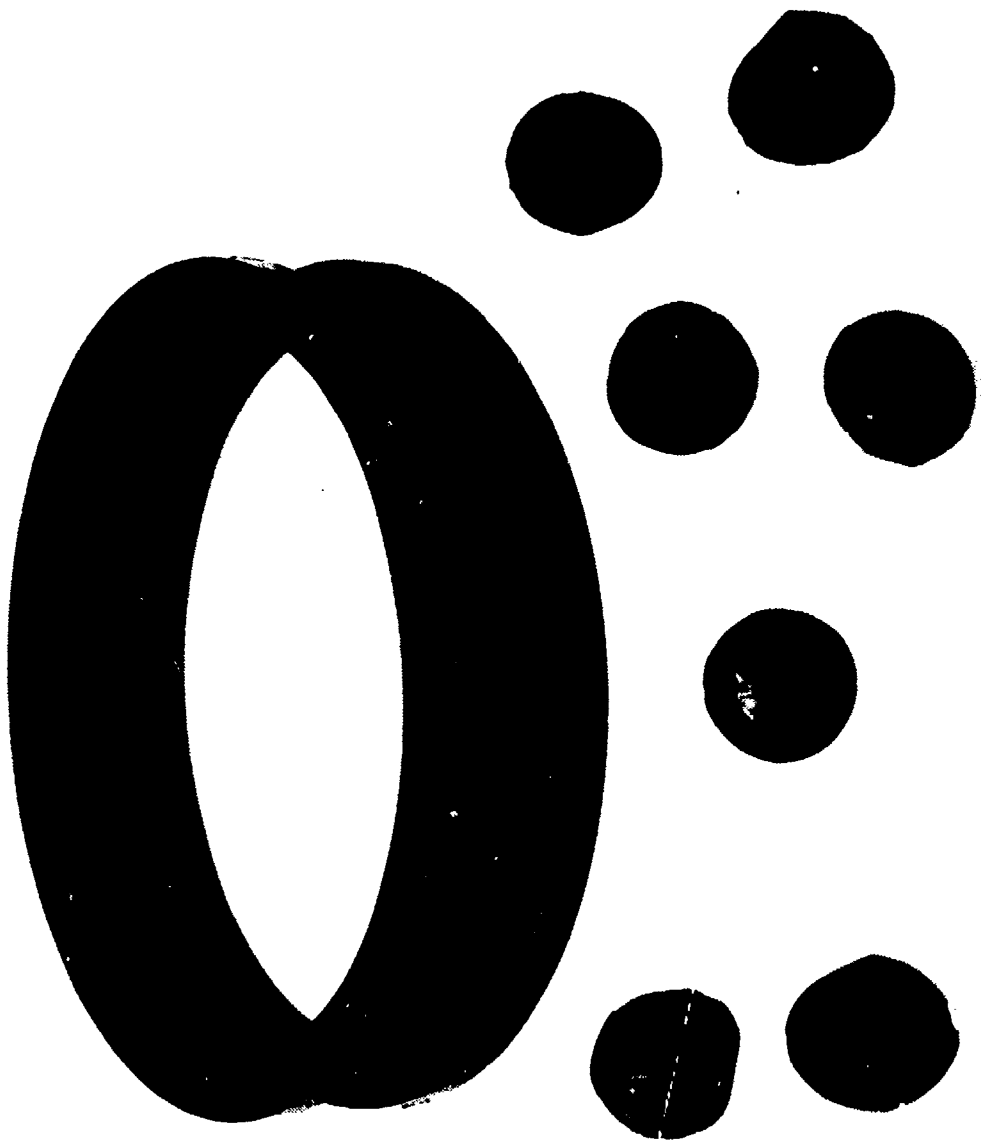


Figure 6-17. Ruptured Hydraulic Line Adapter

F-48871



92180-1

Figure 6-18. Failed Drive-end Bearing

K-10486

Figure 6-19. Broken Magnets

K-10487

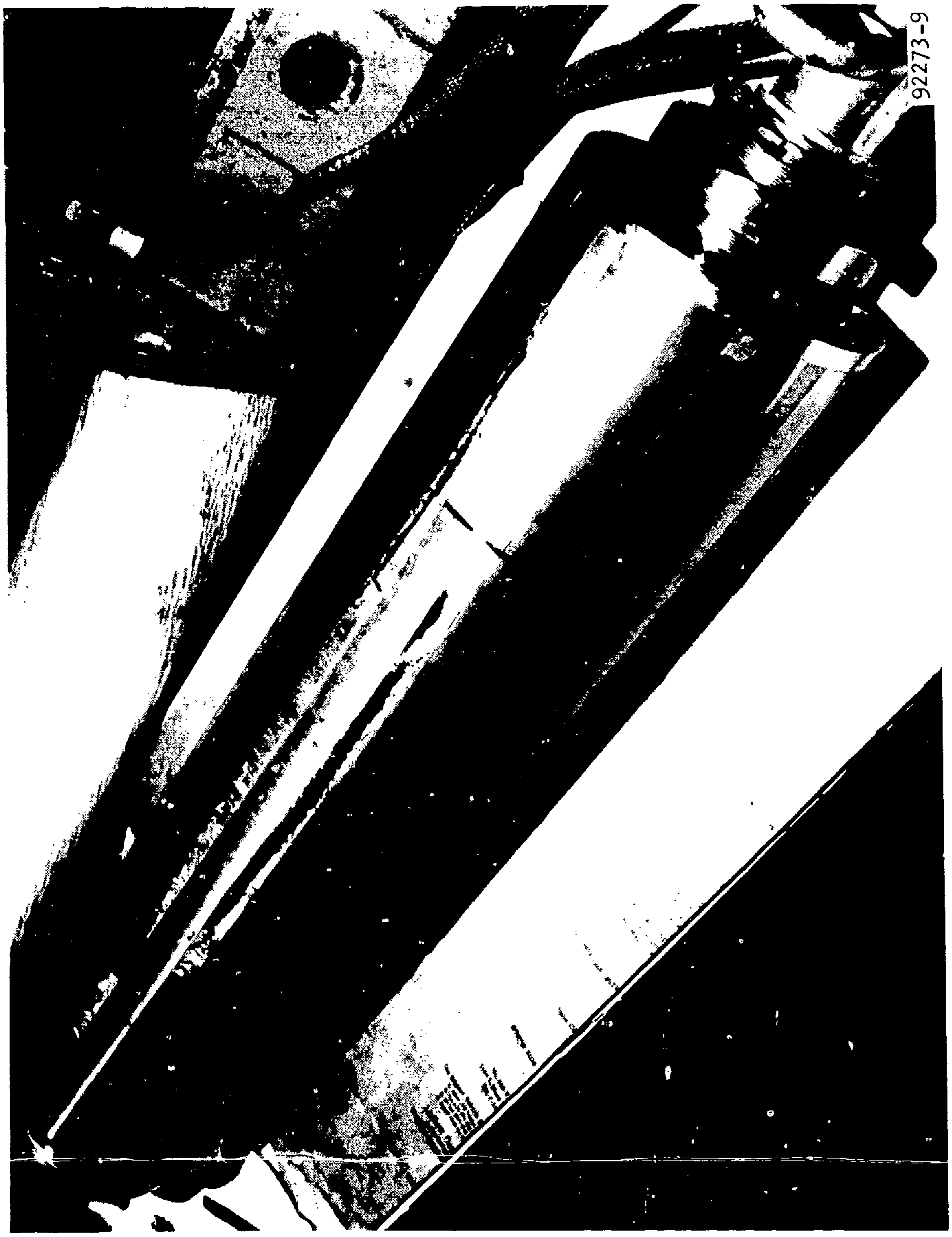


Figure 6-20. Rotor with Damaged Magnets Removed

K-10488

The AiResearch applied mechanics group reviewed the rotor design and failure mode. Stresses in the magnet are relatively high with ideal conditions and are sensitive to configurations of magnet, pole, and the associated contact wedge angle. Stress analysis is based on the assumption that all magnet pieces within the slots behave identically the same during speed increase and decrease. A friction coefficient of $\mu e \geq 0.15$ is required in order to have positive margin for both the tensile and compressive stresses. A course of action was developed to proceed with the rotor program (see Figure 6-21).

Critical component testing in high-risk design areas was completed early in the program and reported in the interim report, submitted in December 1980. The HIP-bonded joint and magnet-pole interfaces were recognized as most critical early in the program. Preliminary tests with a 1-in. long, full-diameter rotor assembly were successful. It was recognized at the time that full-length rotor dynamics might add to magnet and rotor stresses. The 5-mw program was classified as an "advanced state-of-the-art program," in which certain risks were deemed worthwhile in the search for a high-power/lightweight generator. This program developed the longest, cylindrical, high-strength, HIP-bonded joint of dissimilar rotor materials in the world.

The reasons for magnet deterioration are difficult to determine, but some points of comparison may be made between component and end-item testing:

(a) The model was spin-tested in a vacuum chamber spin pit hanging from a flexible shaft, which enabled it to shift to a natural angle of precession as the magnets moved. Therefore G loading of the bearing journals was not a problem. The full size rotor was spun between bearings mounted in a horizontal fixture supported on isolation mounts. G loading as the magnets moved was severe enough to cause one bearing to fail. This vibration was transferred to the magnets within the pole interfaces.

(b) The model used magnets which did not have surface cracks. The full-size rotor used larger magnets which, while the best available at the time, had visible cracks.

(c) The model used 1 magnet per slot, whereas the full-size rotor used 11 magnets per slot.

These differences in scale between experimental, analytical, and full-size development rotors, and the small positive design margin, contributed to the rotor failure. Advances in technology frequently require experimental risks to advance the state of the art.

Captain Neal Harold, Air Force project engineer, reviewed the status of the rotor development program with AiResearch engineering. Captain Harold and Air Force program management concluded that the program should be terminated due to the risk of rebuilding the rotor, and impossibility of completing the rotor within the required program time frame.

AIRESEARCH MANUFACTURING COMPANY

OFFICE MEMO

IN REPLY REFER TO: 59303-45944-001

TO: Andy Druzsba DEPT/MS 93074/T42 EXT: DATE: Nov. 8, 1985

FROM: T. Lee DEPT/MS 93033/T42 EXT: 3602

COPIES TO: E. Brown
F. Echolds
A. Elsayed
R. Graves/
A. Hammoud
[redacted]
F. McCarty
Chrono

SUBJECT: REVIEW OF STRESS IN MAGNETS OF THE 5 MGWA PMG. ROTOR

REF:
1. Calculation Files C-10362, C-11607
2. Memo 89303-39316-006, B. Foster to F. McCarty dated 1/2/78
3. Memo 89303-57408-001, S. Wang to A. Druzsba dated 5/15/83
4. Memo 39303-45944-001. T. Lee to Echolds/Friedericy/Graves/McCarty/Moeller dated 3/25/83.

High vibration were reported during the spin-rig runs at speeds below 14,000 rpm after the subject rotor had reached 19,040 rpm on August 21, 1985. Measurable localized bumps up to 0.070 inch high were recorded on the outside surface of the hoop sleeve. A number of failed magnets along slots #12 and #13 had been found after the hoop sleeve was removed.

Stress analysis performed on the rotor was based on two dimensional analysis of 1/28th of the rotor as shown in Figure 1. The analysis is based on the assumption that all magnet pieces within the slots behave identically the same during speed increase and decrease. This requires the same coefficient of friction at all contact interfaces between the magnets and poles. Plane stress element of ANSYS finite element computer code was employed to predict stresses and displacements of the rotor components. The contact between the magnets and poles was modeled by 2-D interface elements. The nickel bedding material is simulated by the stiffness in the interface element to provide nearly even load distribution of the magnet centrifugal force.

Based on the cited references, important notes are given below:

1. Stresses in the magnet are relatively high with the above ideal condition and are sensitive to configurations of magnet, pole and the associated contact wedge angle.

2. A friction coefficient $\mu_e \geq 0.15$ is required in order to have positive margin for both the tensile and compressive stresses (see Figure 1). Reported strength of magnets is 4.2 ksi to 8 ksi for tensile and 40 ksi for compressive.

3. The analysis did not address residual compressive load after overspeeding.

FORM 784-1 (2-83)

Figure 6-21. Review of Stress in Magnets of 5-mw PMG Rotor

4. Higher stresses will be developed in magnets due to:

   a) Variation of effective friction coefficient.

   b) Geometric imperfection and variation of supporting slots as well as magnets.

   c) Consequence of a) or b) that would cause some magnets to wedge before others.

Additional margin is therefore required to account for the above.

Although the ultimate strength of the magnets has not been verified at AiResearch, failed magnets are believed due to combination of 4 a), 4 b), and 4 c) which would cause stresses in magnets to be higher than originally estimated. Inertia loads induced from the recorded high vibration tends to bend the rotor. However, estimated bending stress developed in magnets is less than 1.6 ksi at 13,000 rpm and 0.6 ksi at 19,000 rpm. These bending stresses are not additive to the high stress location in the magnet resulting from centrifugal effect.

The following additional testing and analysis of the wedge supported permanent magnet rotor design is required in order to improve its reliability.

1. Evaluate speed cycling effect (analysis and test).

2. Obtain residual load and stress after overspeed (test and analysis).

3. Develop a scheme to experimentally screen the magnets, w.r.t. its mechanical strengths, before installation.

4. Analyze the effect of dimensional tolerances in the pole and magnet geometries as well as the variation of friction coefficient from one magnet/pole interface to another.

5. Do not depend on friction to provide positive margin.

Reviewed: A. Elsayed
A. Elsayed
Applied Mechanics Group
Engineering Sciences

T. Lee
T. Lee
Applied Mechanics Group
Engineering Sciences

Approved: Ahmed S. Hammoud
Ahmed S. Hammoud
Manager, Applied Mechanics
Engineering Sciences

/er
Attachments

Figure 6-21. (Continued)

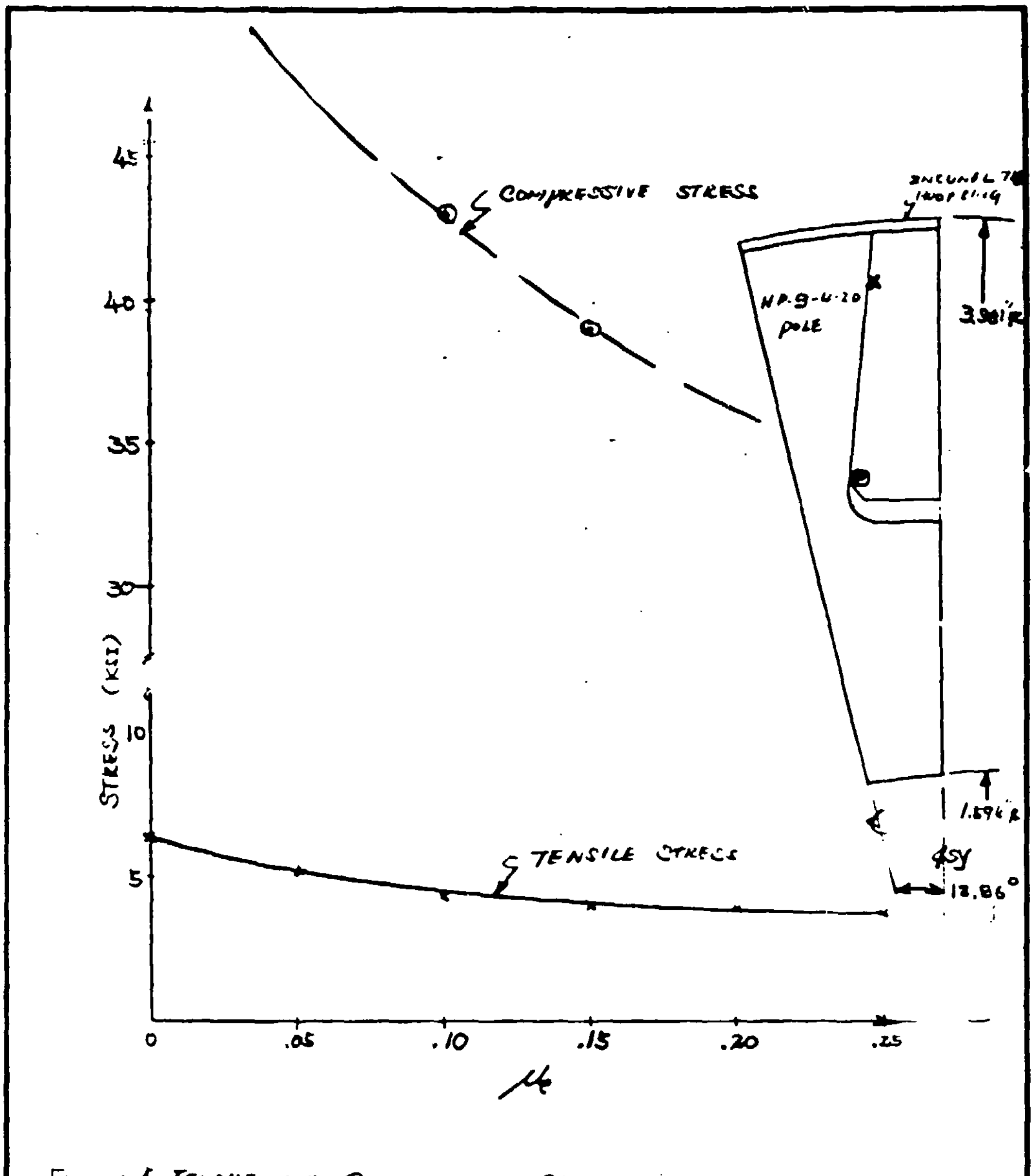
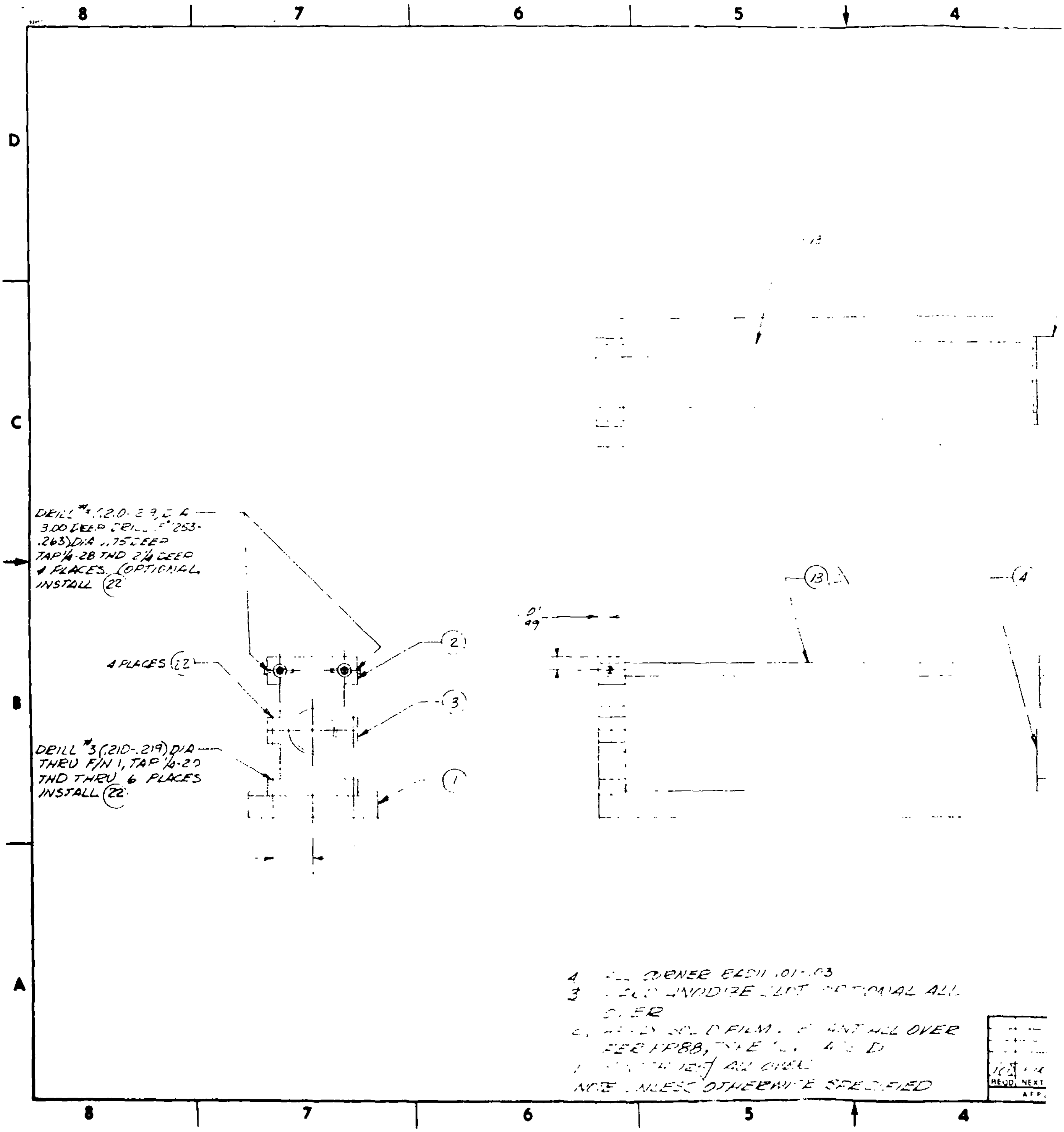


Figure 1: TENSILE AND COMPRESSIVE STRESSES IN MAGNETS OF .5 MEWA PM ROTOR @ OVERSPEED OF 19,800 RPM

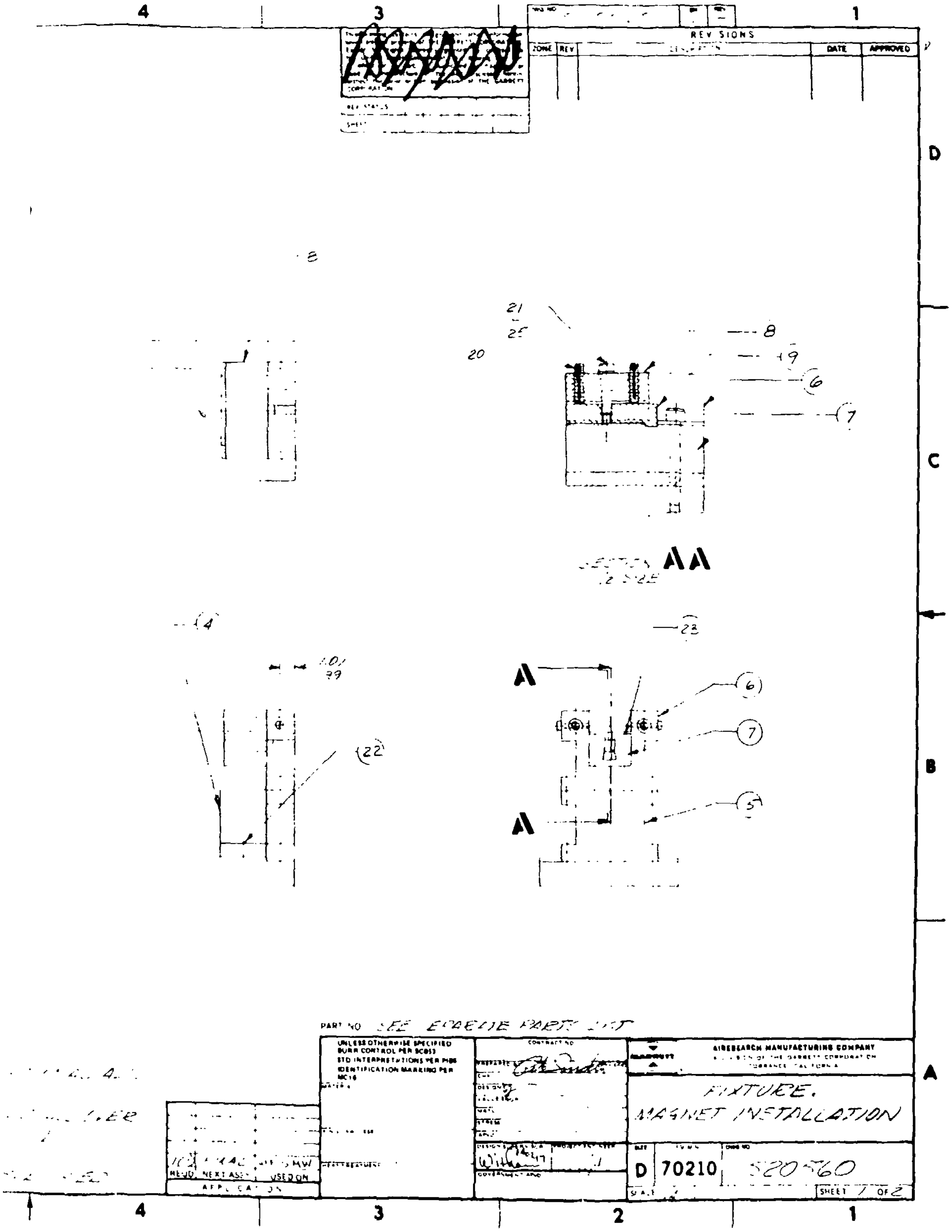
Figure 6-21. (Continued)

APPENDIX

DRAWINGS



AIRESEARCH MANUFACTURING COMPANY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IDENTIFICATION MARKING PER MC16
AIRESEARCH MANUFACTURING COMPANY
TORRANCE, CALIFORNIA
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MAGNET INSTALLATION
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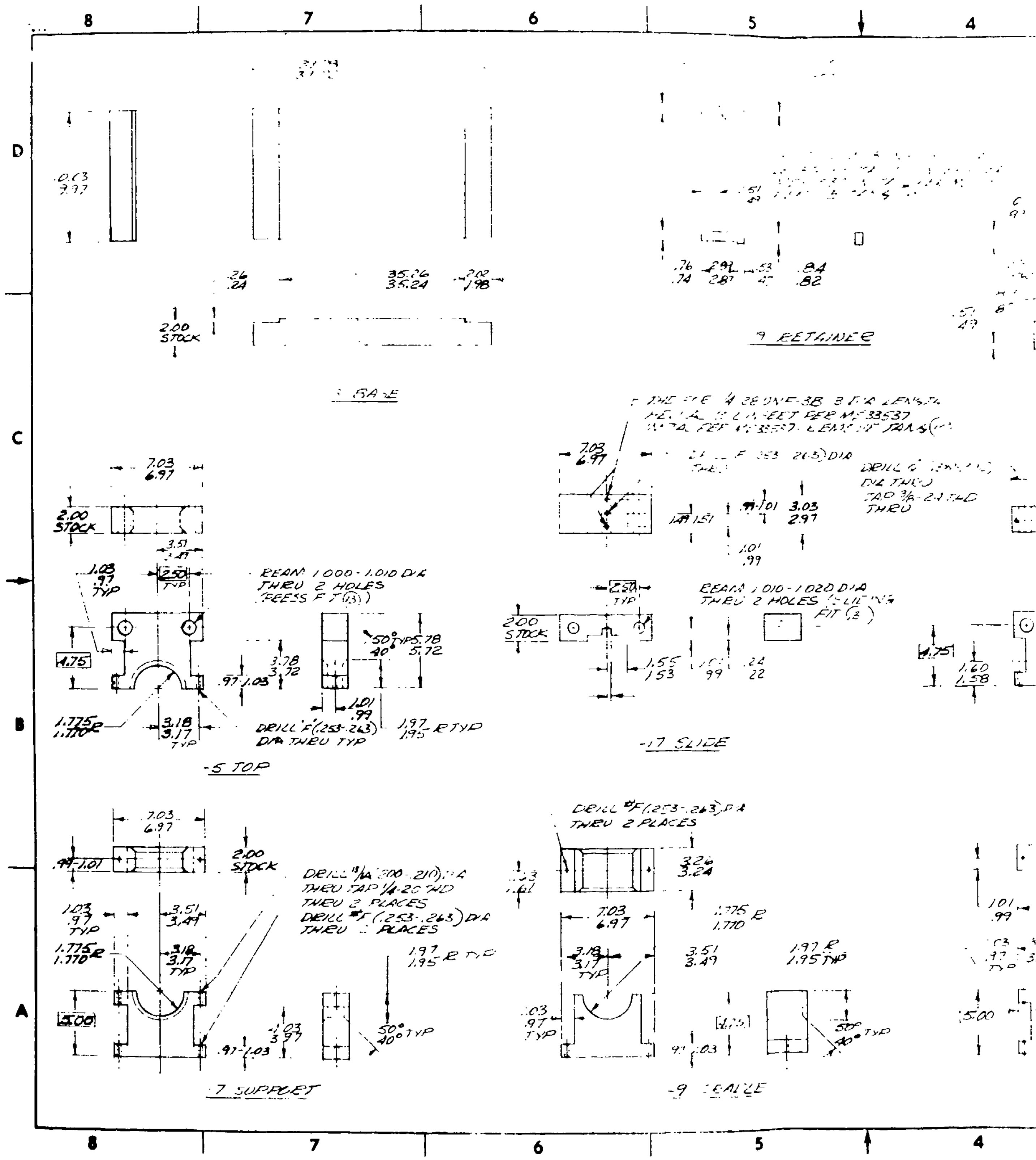
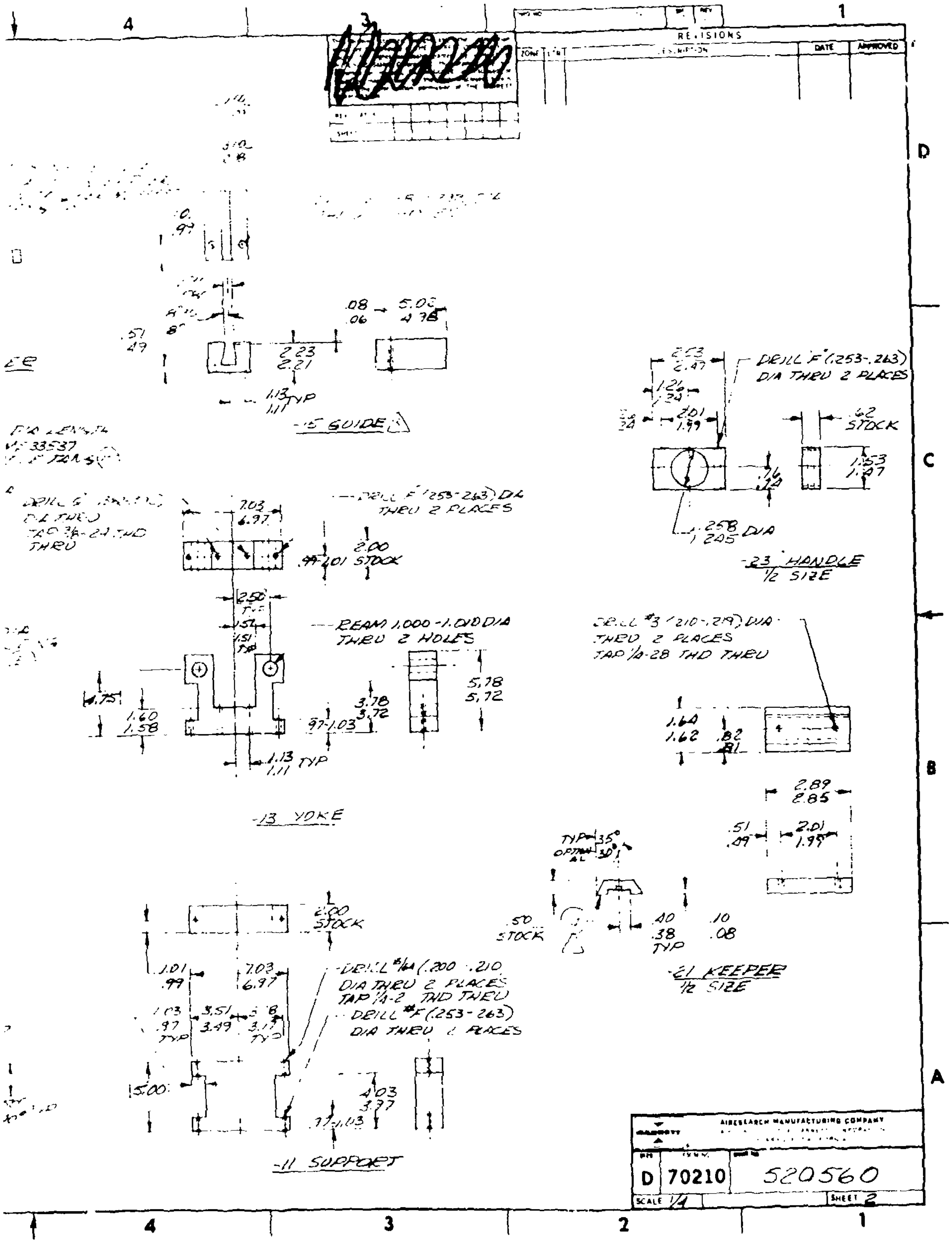


AIRESEARCH MANUFACTURING COMPANY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-13 YOKE
.62 STOCK
-23 HANDLE
1/2 SIZE
DRILL #3 (.210-.219) DIA THRU 2 PLACES TAP 1/4-28 THD THRU
.50 STOCK
-21 KEEPER
1/2 SIZE
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DRILL #F (.253-.263) DIA THRU 2 PLACES
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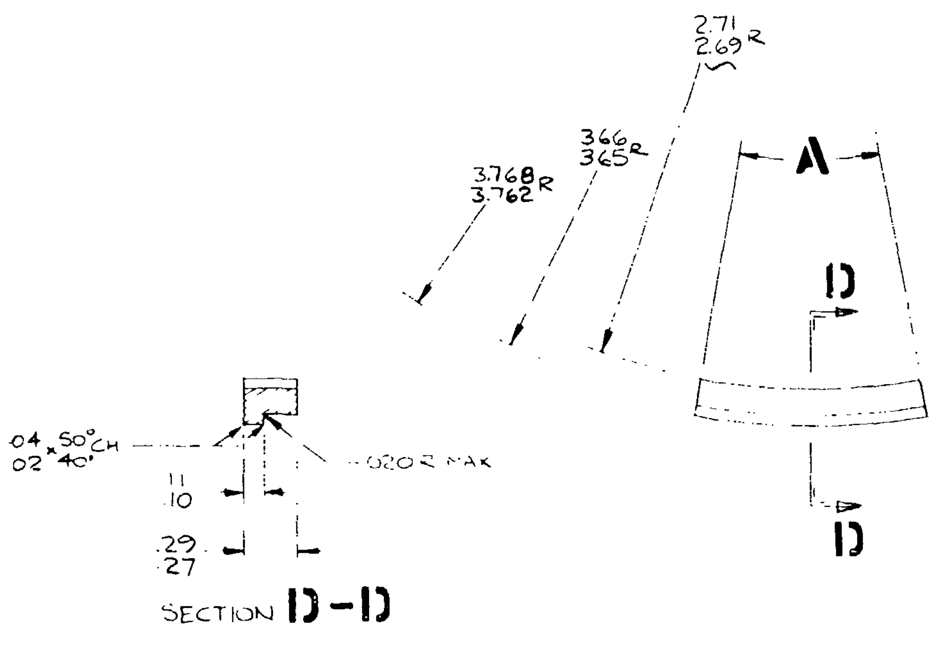
2006958-2	15
2006958-3	20
2006958-4	25



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4(-2)		

APPLICATION

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AIRESEARCH MANUFACTURING COMPANY

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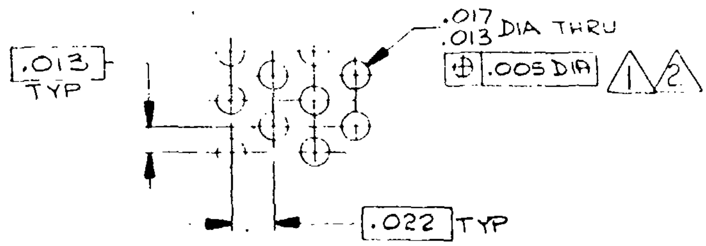

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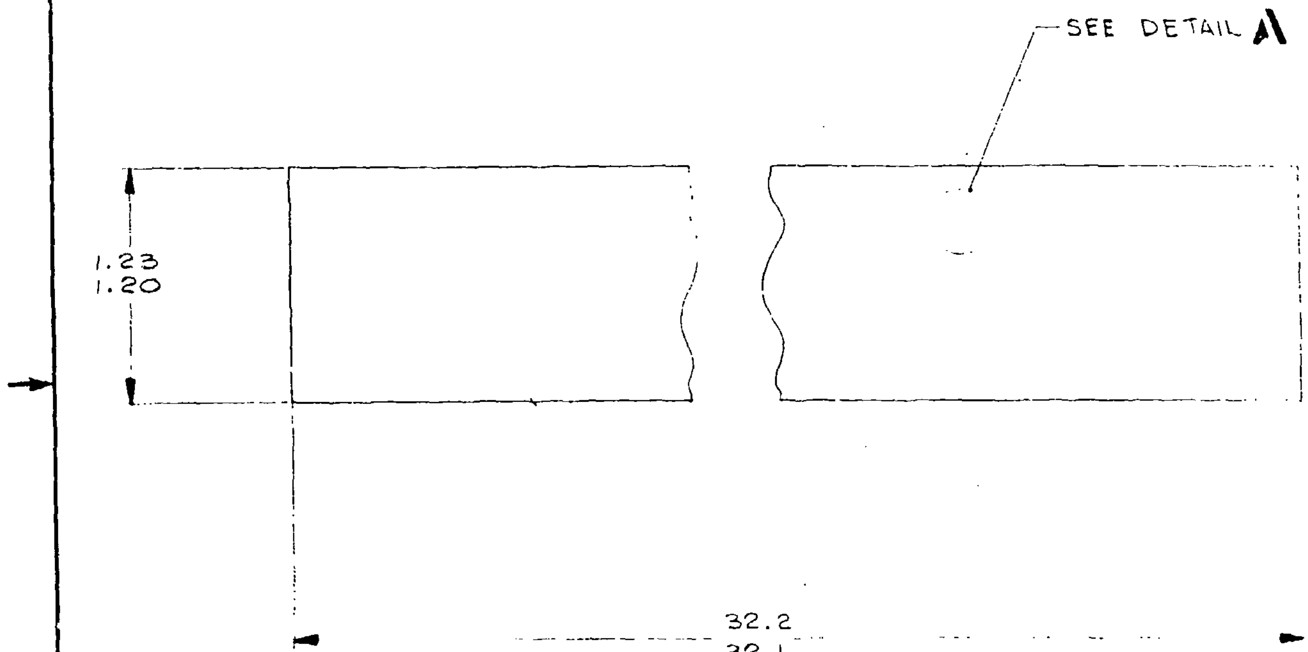

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2. HOLE PATTERN SIMILAR TO 2046699-1

1. PHOTOCHEMICAL ETCH HOLE PATTERN

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APPLICATION

PART NO 2007989-1

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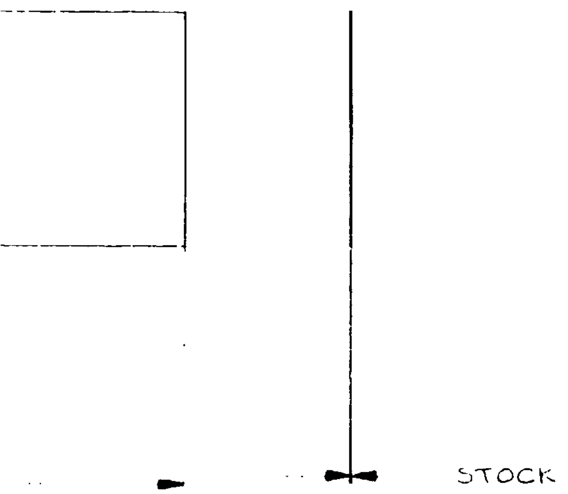

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JA
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CHK 82 12 15
CALCULATIONS 84 03 23

AIRESEARCH MANUFACTURING COMPANY
A DIVISION OF THE GARRETT CORPORATION
TORRANCE, CALIFORNIA

SHIM, MAGNET, ROTOR
(5 MW GENERATOR)

PROJECT ENGINEER
GOVERNMENT APVD

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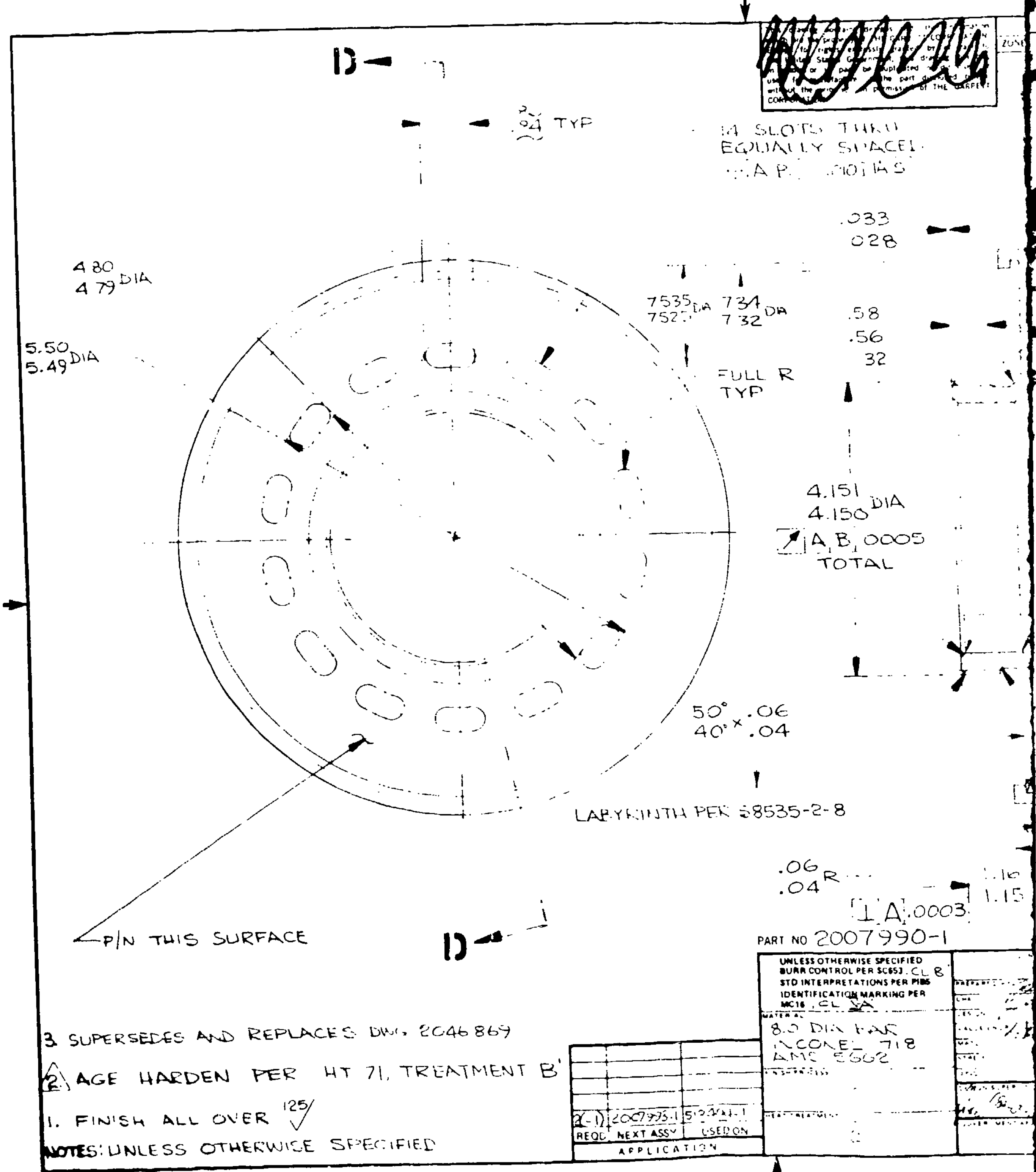

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LABYRINTH PER 58535-2-8
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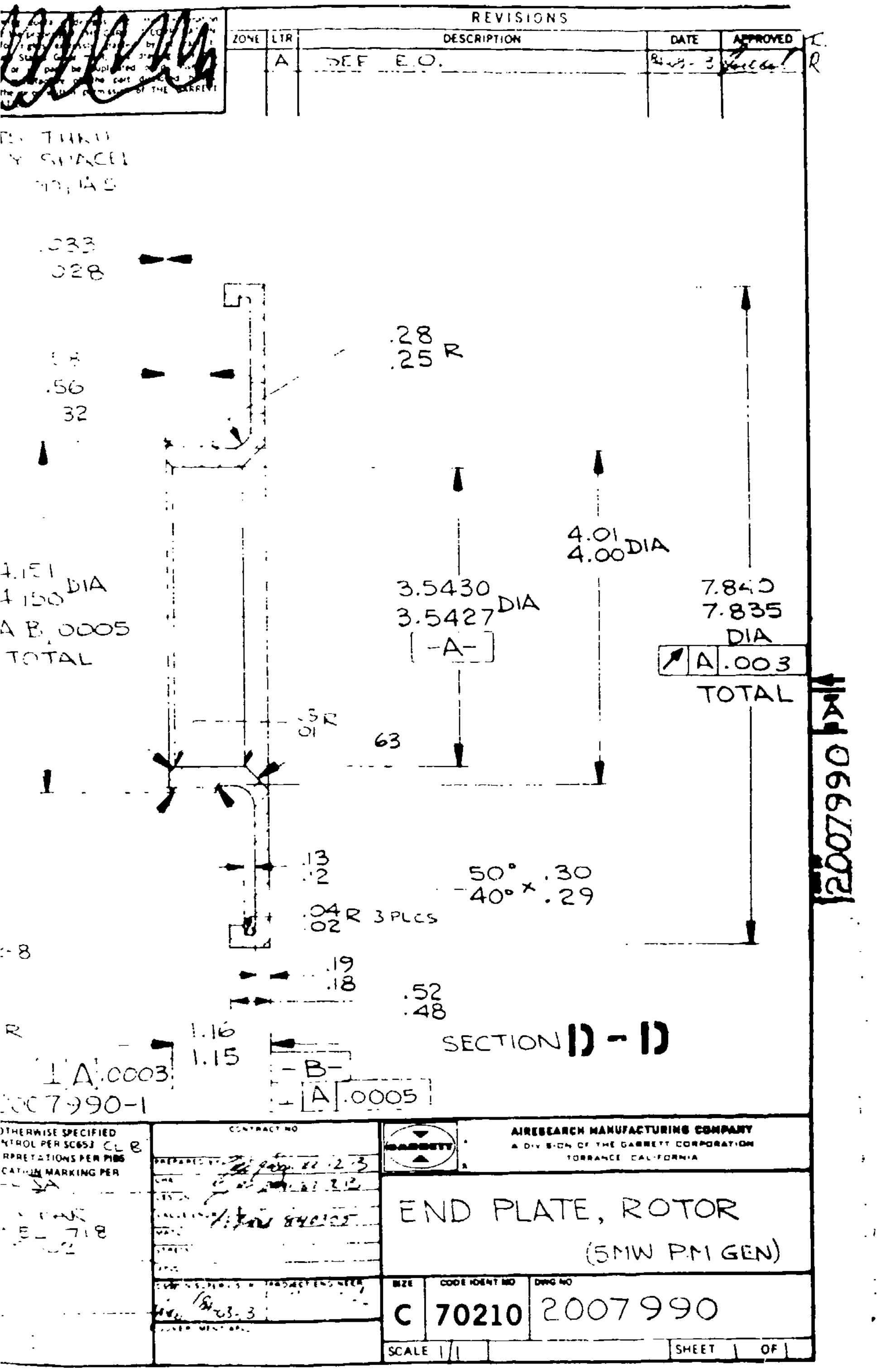
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AIRESEARCH MANUFACTURING COMPANY
A DIVISION OF THE GARRETT CORPORATION
TORRANCE CALIFORNIA
END PLATE, ROTOR
(5MW PM GEN)
SIZE C
CODE IDENT NO 70210
DWG NO 2007990
SCALE 1/1
SHEET 1 OF 1

SH 1

DWG NO 2007988

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   AIRESEARCH ITEM IDENTIFICATION NUMBER 2007988-1
   VENDOR CODE IDENT NUMBER OR TRADEMARK

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SOURCE CONTROL DRAWING

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APVD	
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OTHER ACTIVITY APVD	

AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA
A DIVISION OF THE GARRETT CORPORATION
TORRANCE, CALIFORNIA

MAGNET, GENERATOR

SIZE	CODE IDENT NO	DWG NO
A	70210	2007988

SCALE | SHEET 1 OF 4

FORM 2347 2 (9 76)

6.0 SCOPE

6.1 THIS SPECIFICATION COVERS THE DETAIL REQUIREMENTS FOR FABRICATION OR A RARE EARTH-COBALT PERMANENT MAGNET POLE

7.0 MATERIAL

7.1 THE POLE SHALL BE FABRICATED FROM A SUITABLE MATERIAL TO MEET THE FOLLOWING PROPERTIES.

8.0 MAGNETIC PROPERTIES (MINIMUM)

8.1	RESIDUAL INDUCTION (B_r):	9380 GAUSS
8.2	COERCIVE FORCE (H_c):	8690 OERSTEDS
8.3	ENERGY PRODUCT (B_dH_d) MAX.:	22 X 10^6 GOe

9.0 PHYSICAL PROPERTIES

9.1 DENSITY — 8.3 G/CC (APPROX.)

10.0 MECHANICAL AND STRUCTURAL PROPERTIES:

10.1 TENSILE STRENGTH — 8000 PSI (APPROX.)

10.2 NO CRACKS AND CHIPPING ALLOWED THAT WOULD EFFECT THE BASIC STRUCTURAL INTEGRITY OF THE MAGNET IN THE INTENDED APPLICATION. ACCEPTANCE CRITERIA IS DEFINED IN FIG. 1.

11.0 VENDOR ACCEPTANCE TESTS

11.1 PERFORM VISUAL AND DIMENSIONAL INSPECTION TO DRAWING REQUIREMENTS.

11.2 A B-H CURVE MEASURED ON A REPRESENTATIVE SAMPLE FROM THE MAGNET MATERIAL LOT SHALL BE SHIPPED WITH EACH ORDER.

12.0 MAGNETS TO BE DELIVERED IN FULLY MAGNETIZED STATE.

13.0 REFER TO SIMILAR DWG 2046854

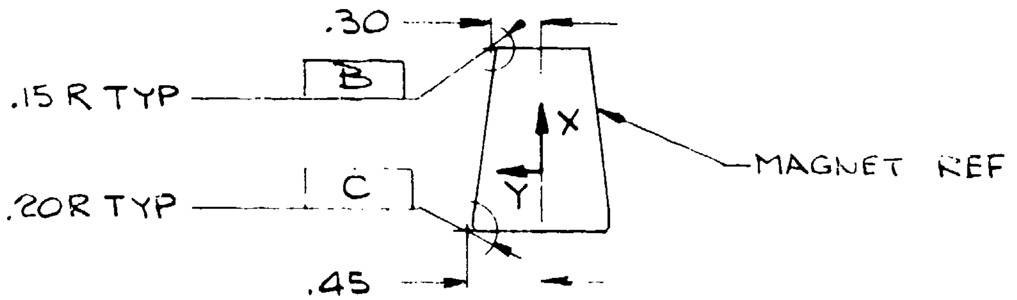
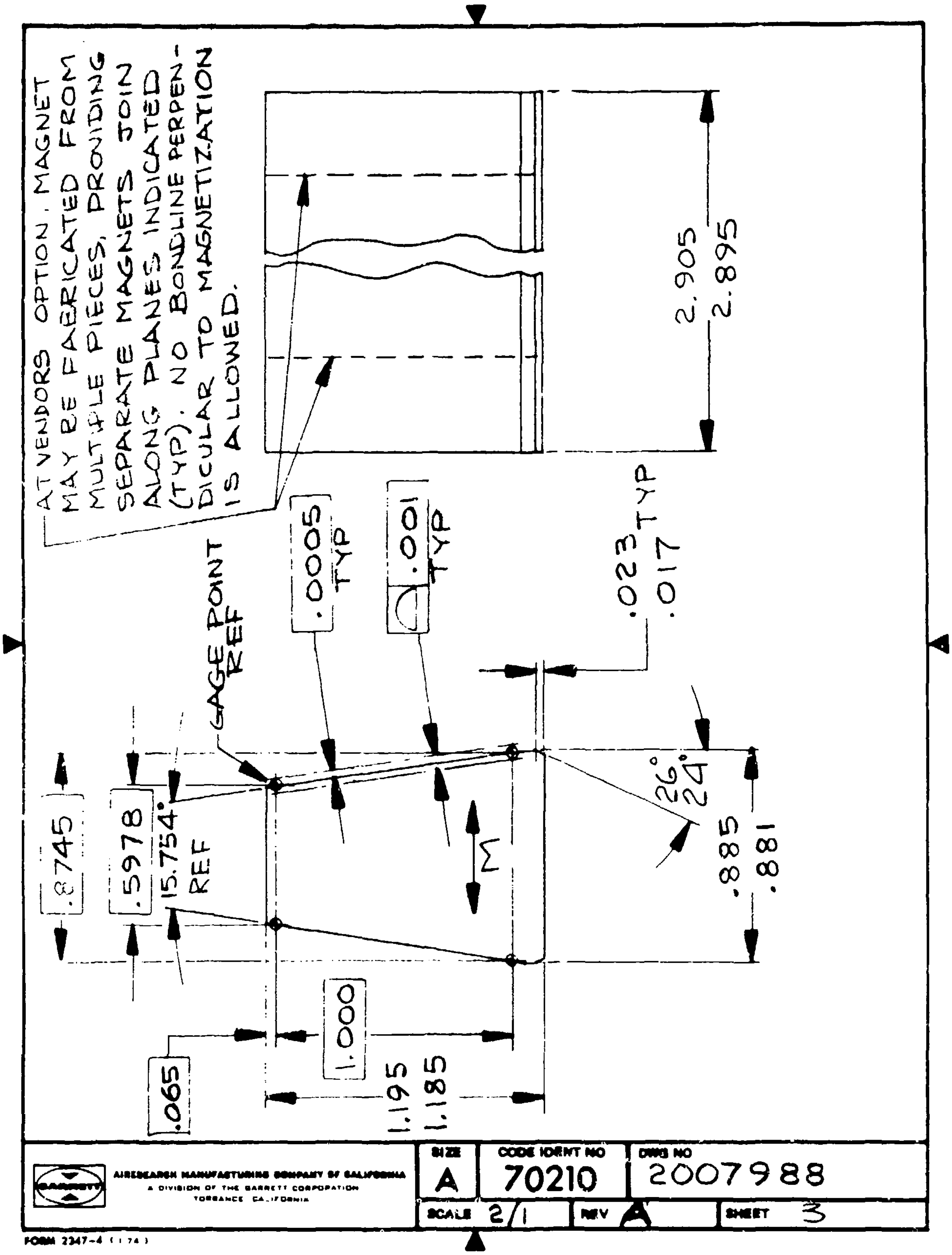


FIGURE 1

NO CRACKS IN CORNERS AS DEFINED BY RADII C & B
OTHER AREA SHALL HAVE NO CRACKS PARALLEL TO Y AXIS ± 30°

AIRESEARCH MANUFACTURING COMPANY OF CALIFORNIA A DIVISION OF THE GARRETT CORPORATION TORRANCE, CALIFORNIA	SIZE A	CODE IDENT NO 70210	DWG NO 2007988
	SCALE NONE	REV —	SHEET 2

FORM 2347-4 (1-74)



☆U.S.Government Printing Office: 1986 — 646-067/40979